# Evaluation of an Australian Landscape Fire Model Applied to a Northern Rocky Mountain Landscape

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**Evaluation of an Australian Landscape Fire Model Applied to a Northern Rocky Mountain Landscape**

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## 1. Introduction

Fire regimes have integral roles in ecosystems throughout the world (Naveh, 1975; Gill *et al.* 1981; Goldammer, 1990; Johnson, 1992; Pyne *et al.,* 1996, Bradstock *et al.*, 2002). Effects of fire regimes on ecosystems could be described in terms of the time between fires, the time since the last fire, the intensity of the fire, the type of fuel burnt and the season of occurrence (Gill, 1975). Fire regimes are characterized by variability (McCarthy and Cary, 2002) insofar as they do not always occur at the same interval, at the same intensity, or at the same time of year. Such variability can have important influences on ecosystems (Cary and Morrison, 1995; Morrison *et al.,* 1995; McCarthy and Burgman, 1995).

The ability to predict the nature of fire regimes across landscapes is limited by the level of complexity that can be included in models, which will ultimately be limited by the level of understanding and knowledge. Our aim in this paper is to implement FIRESCAPE (Cary, 1998; Cary and Banks, 1999; McCarthy and Cary, 2002, Cary, 2002), a process-based model that was developed for predicting fire regimes in the Eucalypt forests of south-eastern Australia, in a northern Rocky Mountain landscape. The rationale for doing this is that the underlying processes affecting fire behaviour, and ultimately fire regimes (Cary, 2002), including those associated with fuel, terrain, weather and ignition patterns, can be applied universally, irrespective of the actual modelling approach adopted, and that there is value in applying a range of approaches in a single study location.

This research is the first step in a larger project involving comparing the results of the Australian model with FIRE-BGC, a model developed specifically for northern Rocky Mountain landscapes. It had been originally anticipated that this comparison could have been completed as part of this RJVA, however, at the time of writing FIRE-BGC has not yet fully been implemented for the agreed study site.

## 2. Study area - Glacier National Park

Glacier National Park lies in northern Montana, USA, adjacent to the border with Canada, straddling the continental divide (Figure 1). It is characterized by significant relief and topographic complexity (Figure 2) and a range of vegetation types and other land cover, including water, barren sites, ice and snow (Figure 3). The western side of the park experiences the influence of moist north Pacific Ocean air masses throughout most of the year while a drier continental climate prevails on the eastern side (Barrett *et al.*, 1991). On the western side of the park, precipitation increases from the north-west to the south-east and with increasing altitude toward the continental divide (Barrett *et al.*, 1991).

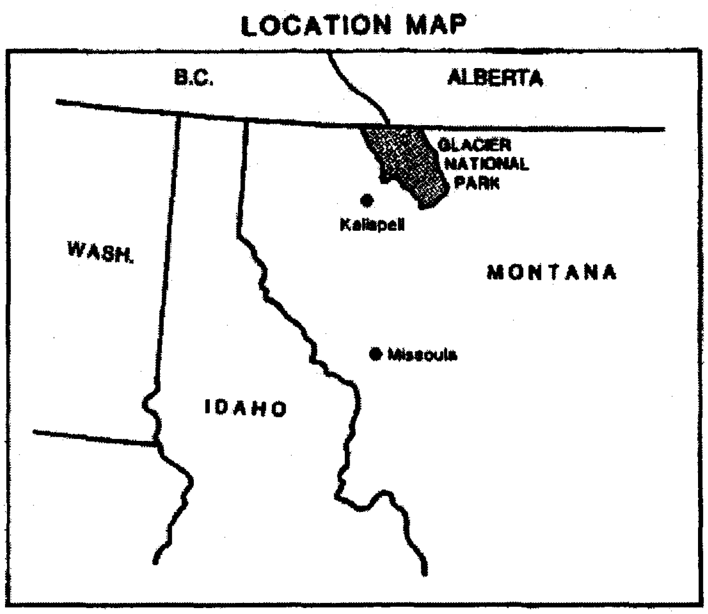


**Figure 1.** Location of Glacier National Park, Montana, USA. (Source: Barrett *et al.*, 1991).

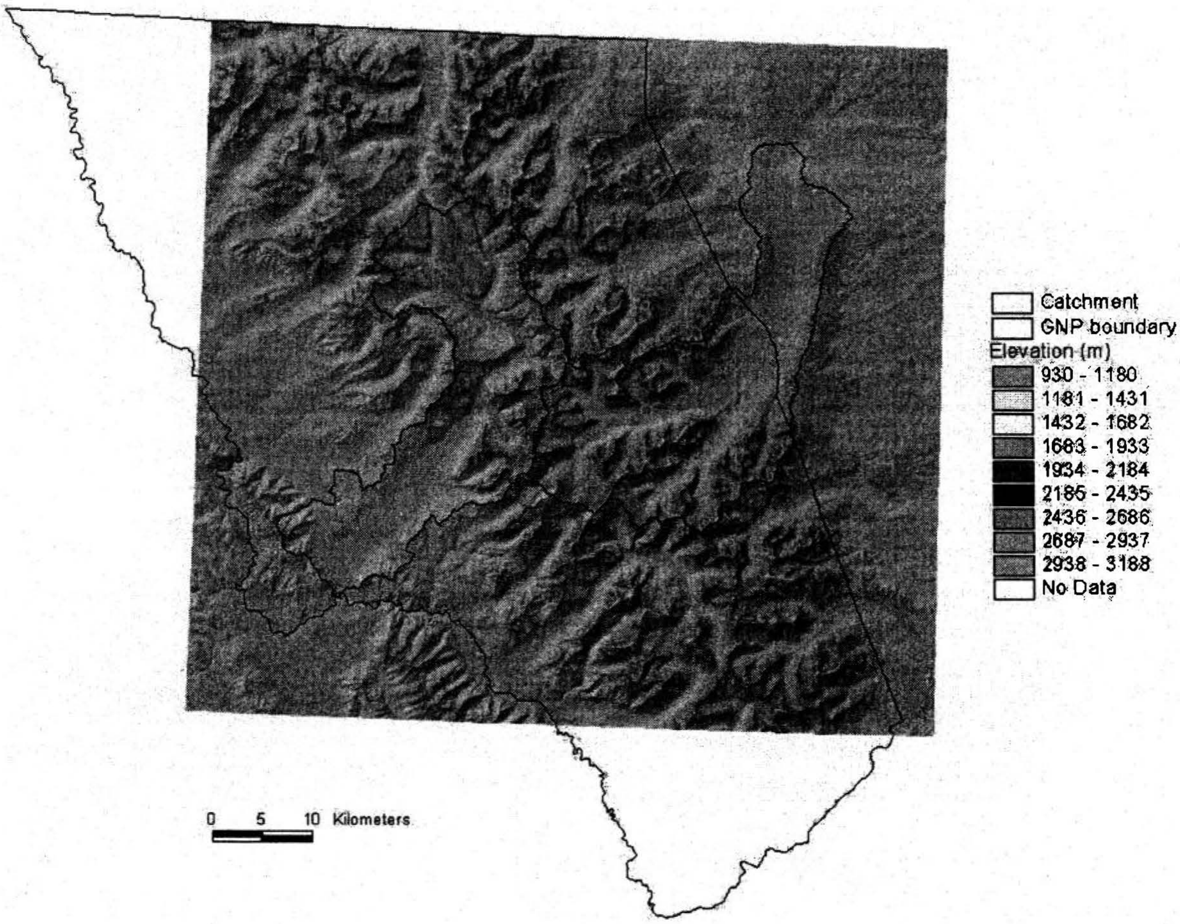


**Figure 2.** Topographic features of Glacier National Park, Montana, USA. The boundaries of the Lake McDonald catchment (west) and St Mary catchment (East) are indicated in blue. The GNP boundary is indicated by the black line.

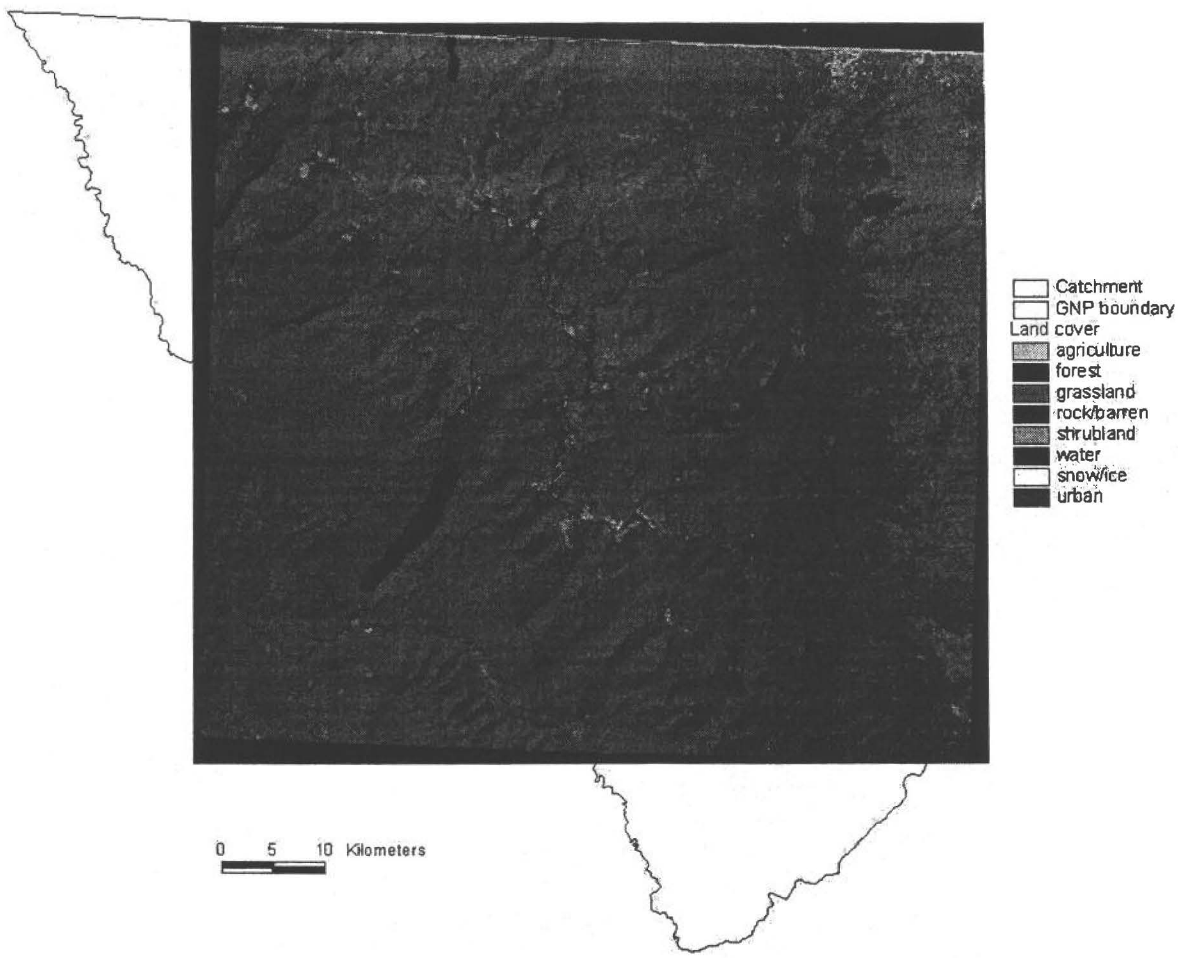


**Figure 3.** Vegetation and land cover of Glacier National Park, Montana, USA. The boundaries of the Lake McDonald catchment (west) and St Mary catchment (East) are indicated in blue. The GNP boundary is indicated by the black line.

## 3. The FIRESCAPE model

Fires can be represented as a series of points across a landscape. Spatial models of fires are generally either mechanistic, simulating the ignition and spread of fires, or footprint models, a statistical representation of fire sizes and shapes (McCarthy and Gill, 1997). FIRESCAPE is a mechanistic or process based model. Spatial patterns of fire regimes are generated by simulating individual fire events that are combined, over time, into patterns of fire frequency, fire intensity and the season of fire occurrence (Cary, 1998; Cary and Banks, 1999).

The model has previously been implemented in the Australian Capital Territory region of south-eastern Australia (Cary, 1998; Cary and Banks, 1999; McCarthy and Cary, 2002) for a range of purposes, including to understand the potential impact of a changing climate in that region (Cary, 2002). FIRESCAPE has also been implemented in the World Heritage Area in south-western Tasmania in southern Australia (King *et al.*, 2003).

The model incorporates:- i) stochastic generation of realistic patterns of daily weather for fire danger modelling using a modification of Richardson's (1981) weather generator; ii) a process-based model for determining the location of lightning ignitions in spatially complex landscapes; iii) a relationship between lightning occurrence and weather patterns; iv) the implementation of Macarthur's fire spread models for landscape modelling; and v) an implementation of an elliptical fire shape approach that has been modified to take into account heterogeneous fuels, topography, and weather and spread on grids of fixed points.

Section 3.1 outlines the method for stochastic generation of daily weather and its extrapolation across the landscape. Section 3.2 outlines the parametrisation of the model for predicting lightning locations according to terrain features. The simple approach to fuel modelling is presented in section 3.3 and the algorithms for spreading fires and extinguishing fires is presented in section 3.4.

### 3.1 Stochastic Weather Generator for Fire Danger Modelling

*Background*

Forward rate of spread of fires is determined in FIRESCAPE from the fire behaviour algorithm associated with the McArthur Forest Fire Danger Meters (McArthur, 1967; Noble *et al.*, 1980). The inputs to the Forest Fire Danger Index are related to precipitation, temperature, relative humidity and wind speed. These are modelled on a daily time step, using a modified version of the Richardson (1981) weather generator, and interpolated to hourly time steps using simple interpolative techniques. An alternative approach is to use observed daily weather sequences, however, obtaining suitably long sequences of weather data for these purposes can be somewhat problematical (Keane *et al.*, 1996), and while using observed data allow the parameterisation of fire danger and fire behaviour models, they give results based on only one realisation of the weather process. However, it may be

"desirable to generate synthetic sequences of weather data based on the stochastic structure of the meteorological process" (Richardson, 1981) for multiple simulation runs. In this section, a previously modified version of the Richardson weather generator (Cary 1998) is implemented for St Mary, Glacier national Park, and tested against observed data.

*Richardson Weather generator*

Most stochastic weather generators are structured along the lines of that developed by Richardson (1981). Weather is generated in two steps. The first is to model the occurrence and amount of precipitation, followed by the second step which is to model the remaining weather variables conditioned on whether the day is wet or dry.

Initially, a first-order Markov chain (proposed by Gabriel and Neuman (1962)) with only two states, wet or dry, is used to generate sequences of wet and dry days. A day is considered wet if it has a rainfall of 0.2 mm or greater. If the probability of a wet day on day *i* given a wet day on day *i - 1* is denoted as $P_i(W / W)$ and the probability of a wet day on day *i* given a dry day on day *i - 1* is denoted $P_i(W / D)$, then

$$P_i(D / W) = 1 - P_i(W / W) \qquad \text{equation 1}$$

$$P_i(D / D) = 1 - P_i(W / D) \qquad \text{equation 2}$$

Next, Richardson (1981) synthesised the amount of precipitation on wet days using an exponential distribution (Todorovic & Woolhiser, 1974), but points out that this was only used for simplicity. An even simpler approach, adopted in this study, is to randomly sample from a cumulative distribution of precipitation amounts on wet days.

Finally, in order to model the remaining weather variables using the Richardson (1981) generator, observed maximum temperature, minimum temperature and solar radiation sequences are initially transformed into residuals with zero mean and unit variance using monthly summary statistics. Since the residuals are generally dependent in time, and the three series mutually interdependent, the serial correlation coefficients and the cross-correlation coefficients of the series are calculated as descriptions of the time dependence and interdependence respectively (Richardson, 1981). Series of residuals are generated using the weakly stationary generating process of Matalas (1967) by

$$\chi_{p,i}(\mathrm{j}) = \mathrm{A}\chi_{p,i-1}(\mathrm{j}) + B\varepsilon_{p,i}(\mathrm{j}) \qquad \text{equation 3}$$

where $\chi_{p,i}$(j) and $\chi_{p,i-1}$(j) are (3×1) matrices for days *i* and *i - 1* of year p whose elements are residuals of maximum temperature (j=1), minimum temperature (j=2) and solar radiation (j=3); $\varepsilon_{p,i}$(j) is a (3×1) matrix of independent random components that are normally distributed and with a mean of zero and a variance of unity; and A and B are (3×3) matrices whose elements are defined such that the new sequences have the appropriate serial

correlation and cross-correlation coefficients. The A and B matrices may be determined by the following equations

$$A = M_1 M_0^{-1} \qquad \text{equation 4}$$

$$BB^T = M_0 - M_1 M_0^{-1} M_1^T \qquad \text{equation 5}$$

where $M_0$ and $M_1$ are the lag 0 and lag 1 co-variance matrices (or in this case, matrices containing the cross-correlation coefficients given that the three series each has a zero mean and unit variance). $BB^T$ is decomposed via a Cholesky decomposition. The elements of $\chi_{p,i}(j)$ are back transformed, using the appropriate monthly mean and standard deviation, to provide new weather variables on day i. Tests of the model using data from Spokane, Atlanta and Temple (USA) found that generated data compared closely with observed data in rainfall amounts, occurrence of wet days, mean daily temperatures and solar radiation (Richardson, 1981). The Richardson model was slightly modified (and called WGEN), in so far as the two parameter gamma distribution was used in place of the exponential model for rainfall amounts, and the parameters calculated for 139 stations in the United States (Richardson & Wright, 1984).

*Parameterisation of the model for St Mary, Glacier National Park*

The Richardson model was parameterised for St Mary, Montana, using 9 years (1993 – 2001) of daily weather data. The six other weather variables were:- ($j$=1) daily maximum temperature; ($j$=2) daily minimum temperature; ($j$=3) west to east windspeed; ($j$=4) south to north windspeed; and ($j$=5) atmospheric vapour pressure. Atmospheric vapour pressure ($E_a$), rather than relative humidity, is modelled because it is $E_a$ which is a characteristic of the air masses that influence weather not relative humidity which is a function of $E_a$ and the saturated vapour pressure ($E_s$) which is temperature dependent and hence depends on the time of day that the meteorological measurements are taken. All data were recorded at the St Mary RAWS weather station.

Monthly variations in $P_i(W/W)$ and $P_i(W/D)$ in St Mary are indicated in Figure 4. The cumulative distribution of precipitation amount on wet days is given in figure 5. $M_0$ and $M_1$ are given in Table 1.

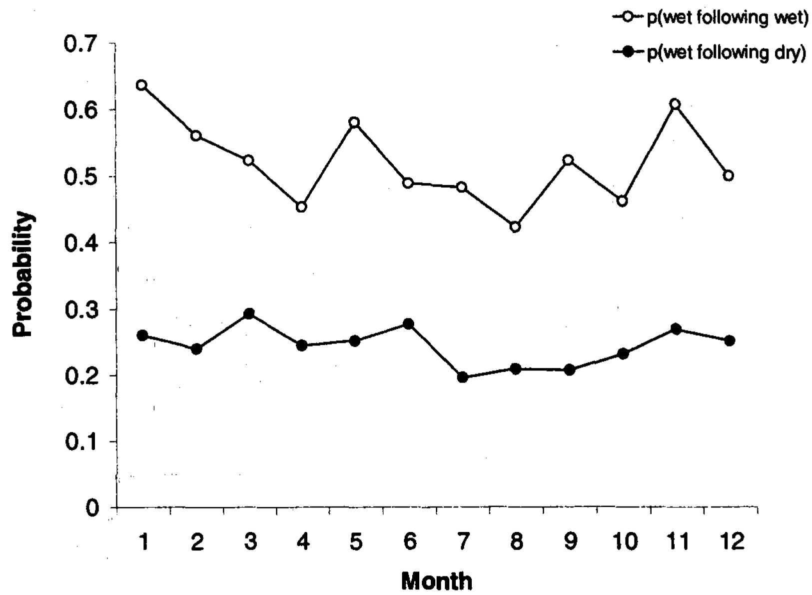


**Figure 4.** Monthly (January =1, February = 2, ..., December = 12) variation in the probability of a wet day following a wet day *P(W/W)* and the probability of a wet day following a dry day *P(W/D)* for the parameterisation of the Richardson stochastic weather generator for fire danger modelling using data from St Mary, Montana.

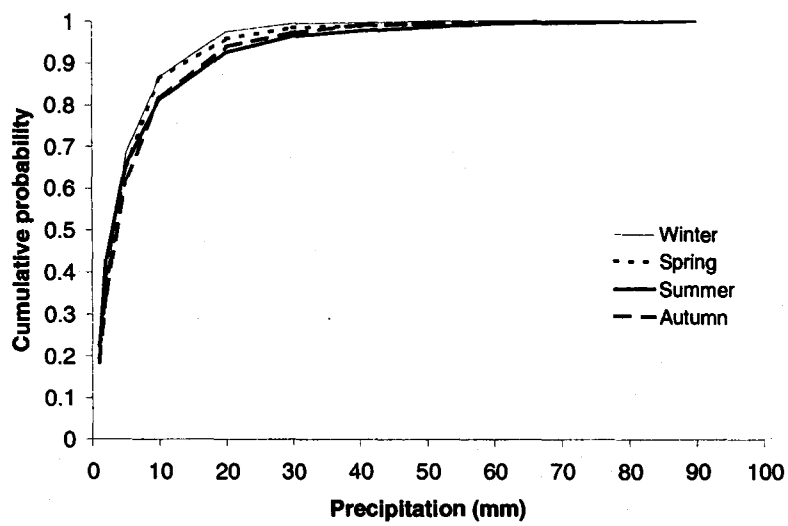


**Figure 5.** Cumulative probability of precipitation amount on wet days by season for the parameterisation of the Richardson stochastic weather generator for fire danger modelling using data from St Mary, Montana.

**Table** 1. (a) Lag 0 ($M_0$) and (b) lag 1 ($M_1$) co-variance matrices for the parameterisation of the Richardson stochastic weather generator for fire danger modelling using data from St Mary. Weather variables are:- ($j$=1) daily maximum temperature; ($j$=2) daily minimum temperature; ($j$=3) W-E windspeed; ($j$=4) S-N windspeed; and ($j$=5) Atmospheric vapour pressure.

| (a) $M_0 =\ j$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | 1.00000 | 0.57933 | 0.15553 | 0.15242 | 0.35008, |
| | 0.00000 | 1.00000 | 0.32478 | 0.32985 | 0.53286, |
| | 0.00000 | 0.00000 | 1.00000 | 0.64292 | -0.01138, |
| | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.01467, |
| | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 |

| (b) $M_1 =\ j$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | 0.74338 | 0.44125 | 0.14087 | 0.19538 | 0.26903, |
| | 0.60040 | 0.59285 | 0.29355 | 0.38934 | 0.46451, |
| | 0.13596 | 0.18462 | 0.45946 | 0.36530 | 0.06132, |
| | 0.07525 | 0.12325 | 0.27525 | 0.48523 | 0.04152, |
| | 0.29924 | 0.34816 | 0.00933 | 0.06899 | 0.67195] |

*Evaluation of the weather generator*

The modified Richardson model was used to simulate 10 years of daily weather for St Mary. The daily Soil Dryness Index (Mount, 1972) and the FFDI was calculated from this data using the daily maximum temperature. The proportion of days in each FFDI unit class (low, moderate, high, very, extreme) in the observed and modelled data set were calculated using all data (Figure 6) and for summer data only (Figure 7). The weather generator generates synthetic weather that matches the distribution of fire danger rating well.

Of equal importance, however, is the ability of the weather generator to produce sequences of fire weather that mimic reality. The length of runs of days with 'low' FFDI (FFDI < 5), days with 'moderate' FFDI (5 < FFDI < 12), and days with 'high' FFDI (12 < FFDI < 24) was compared between the modelled and observed weather (Figures 8 to 10). Runs of days with other FFDI was not made because of the rareness of these runs in both the observed and modelled data. The distributions for modelled weather matched the general shape of the distributions for observed weather, although the model overpredicts the frequency of short

runs in each of the fire danger classes. Nevertheless, the weather simulator was considered sufficiently accurate for the purposes required in this study.

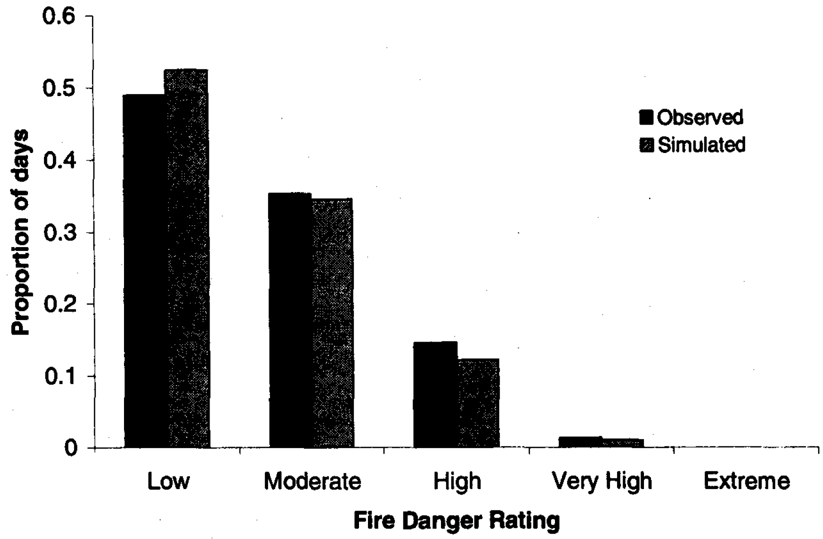


**Figure 6.** Proportion of days from observed and simulated weather for St Mary, Montana, in each of the five fire danger rating classes.

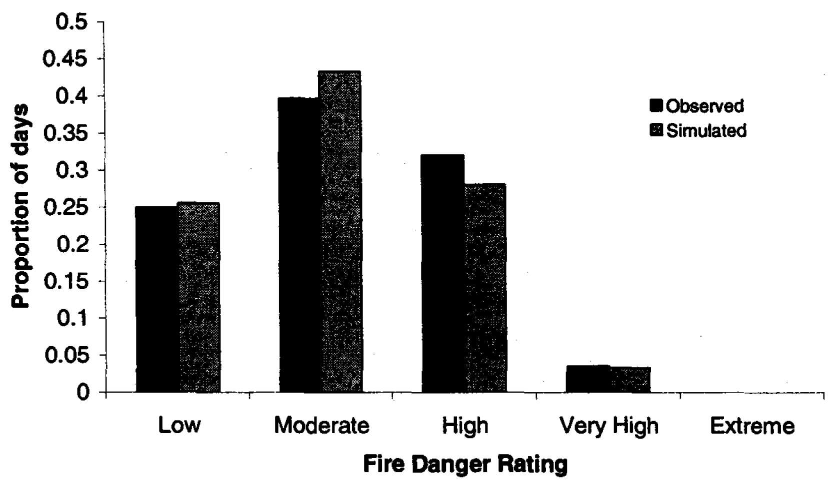


**Figure 7.** Proportion of days from observed and simulated summer weather for St Mary, Montana, in each of the five fire danger rating classes.

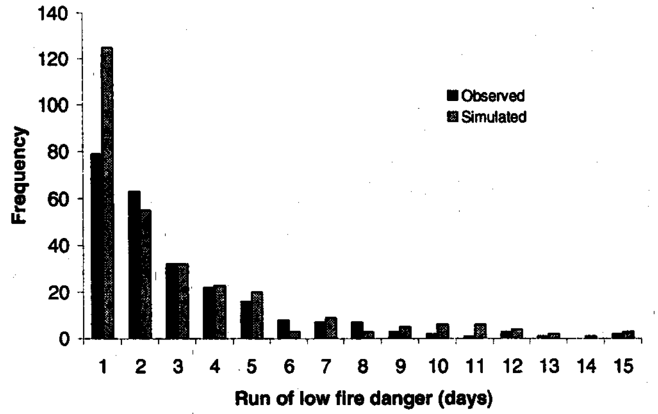


**Figure 8.** Frequency of runs of low fire danger days of varying length from observed and simulated weather for St Mary, Montana.

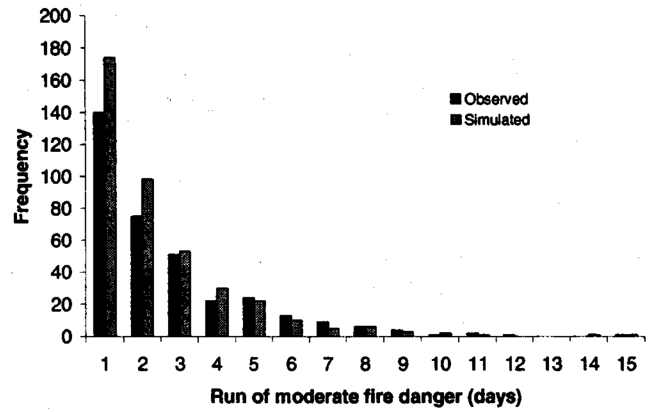


**Figure 9.** Frequency of runs of moderate fire danger days of varying length from observed and simulated weather for St Mary, Montana.

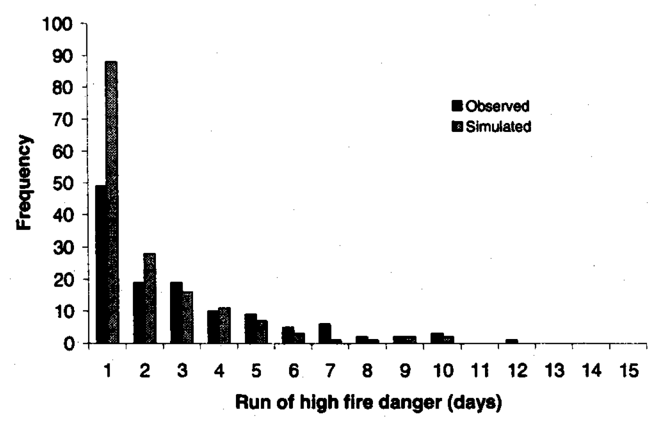


**Figure 10.** Frequency of runs of high fire danger days of varying length from observed and simulated weather for St Mary, Montana.

*Discussion*

The stochastic weather model is a useful tool for simulating realistic sequences of daily fire danger. The model can generate replicate weather sequences that are different realisations of an underlying stochastic process. Therefore, the idiosyncrasies of the observed weather pattern will not affect the results that arise from the application of the weather data in a model system. Further, given the close matching of the frequency distributions of FFDI for observed and modelled weather, it can be concluded that developing a more process-based weather model would not result in the production of more realistic weather sequences.

It is worth noting that the FFDI values generated by the weather model are based on average daily windspeeds. In FIRESCAPE, windspeeds vary throughout the day with windspeeds being higher than average in the afternoons and lower than average at night.

Examples of modelled FFDI sequences for summer are presented in Figure 11. The modelled and observed FFDI show considerable day to day variation and a generally increasing FFDI from the start to the end of summer, as would be expected.

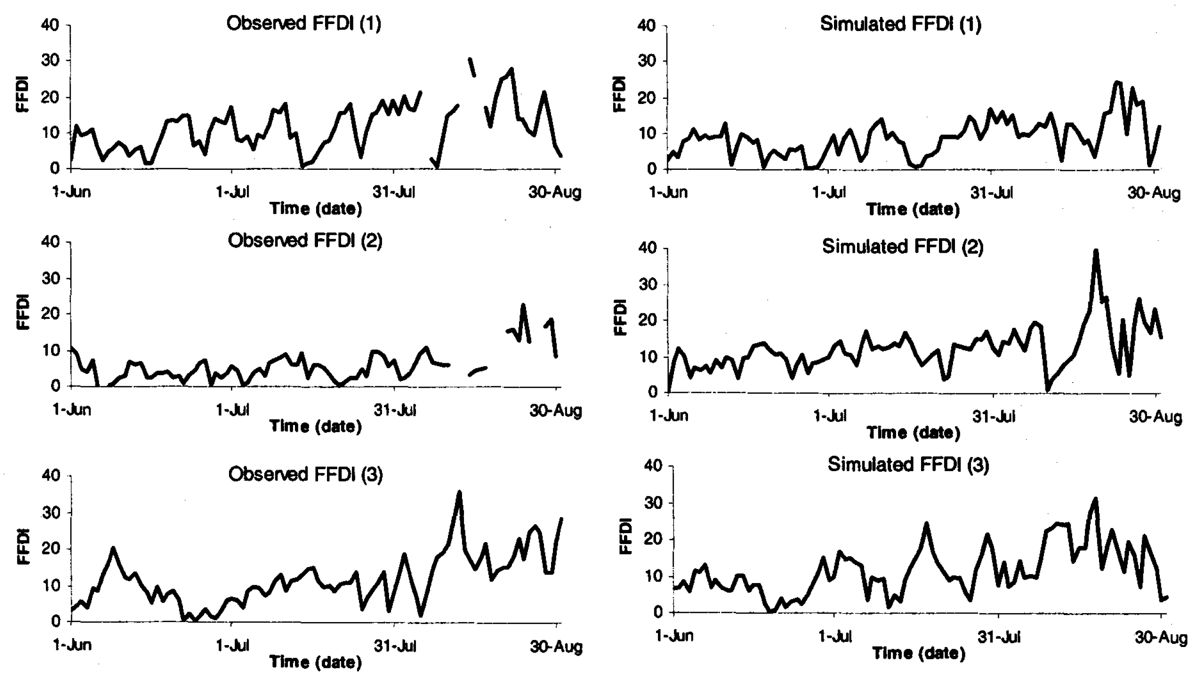


**Figure 11.** Sequences of observed (left hand side) and simulated (right hand side) daily FFDI during summer for St Mary, Montana.

*Extrapolation of meteorological variables across the landscape*

Meteorological variables are calculated for each pixel, as it burns, by extrapolating variables from the St Mary reference site. Maximum temperature and minimum temperatures are adjusted according to lapse rates of 0.73 °C and 0.65 °C per 100 m increase in elevation respectively (Cary, 1998). Atmospheric vapour pressure is not varied with elevation, however, given that saturated vapour pressure increases with temperature, relative humidity generally increases with increasing elevation. Wind speed and direction (W-E wind speed and S-N windspeed) undoubtedly vary because of terrain, however, in FIRESCAPE the regional values are extrapolated across the landscape because of the complexity of modelling wind-terrain interactions and the relative paucity of data available to parameterize a model of this nature.

Precipitation is varied as a function of elevation and longitude. Table 2 presents annual precipitation, elevation and latitude (as eastings in UTM coordinates) for x weather stations in the Glacier National Park region. A linear regression model was fitted to transformations of these data using least squares fitting (Equation 6). Figure 12 depicts the relationship between predicted and observed precipitation ratio, where precipitation ratio is defined as the ratio of annual precipitation at the site of interest to annual precipitation at St Mary.

**Table** 2. Easting (UTM), elevation (m), annual precipitation (mm), E_ratio (ratio of site elevation to elevation of St Mary, and PPT_ratio (ratio of annual precipitation of site to annual precipitation at St Mary), for weather stations in the Glacier National Park region, Montana.

| | Easting (UTM) | Elevation (metres) | Annual precipitation (mm) | E_ratio | PPT_ratio |
|---|---|---|---|---|---|
| St Mary | 321138 | 1390 | 683 | 1.000 | 1.000 |
| Browning | 351224 | 1332 | 379 | 0.958 | 0.555 |
| Babb | 327892 | 1359 | 459 | 0.978 | 0.673 |
| East Glacier | 336095 | 1466 | 734 | 1.054 | 1.074 |
| Summit | 325782 | 1588 | 1013 | 1.142 | 1.483 |
| Essex | 307124 | 1152 | 1022 | 0.828 | 1.496 |
| Hungry Horse Dam | 230000 | 960 | 841 | 0.690 | 1.231 |
| West Glacier | 279628 | 960 | 746 | 0.690 | 1.092 |
| Polebridge | 210000 | 1125 | 558 | 0.809 | 0.817 |
| Flat Top | 290722 | 1920 | 1750 | 1.3817 | 2.563 |
| Many Glacier | 304183 | 1493 | 1239 | 1.074 | 1.814 |
| Emery | 283036 | 1326 | 1041 | 0.953 | 1.523 |
| Pike | 326961 | 1807 | 1255 | 1.300 | 1.836 |

$$PPT\_ratio = -1.11 + 2.315 \times E\_ratio - 0.016 \times (SiteX - SMX)/10000 \qquad r^2 = 0.58$$

Equation 6

Where:

PPT_ratio is the predicted ratio of annual precipitation of site to annual precipitation at St Mary;

E_ratio is the ratio of site elevation to elevation of St Mary;

SiteX is the Easting of the site (UTM); and

SiteY is the Easting of St Mary (UTM).

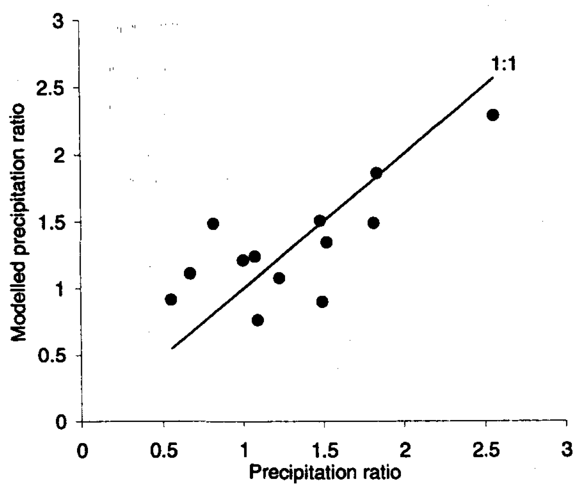


**Figure 12.** Modelled versus observed precipitation ratio, defined as ratio of annual precipitation at the site of interest to annual precipitation at St Mary, for a number of locations in the Glacier National Park region, Montana.

The model for predicting the ratio of annual precipitation at the site of interest to the annual precipitation at St Mary performs reasonably well. It should be noted that the data from Flat Top represents an influential outlier (observed and predicted ratio of annual precipitation round 2.5) in the model. Nevertheless, given that the data was presumably collected from an accurate AWS, and that much higher annual precipitation is expected at such a high elevation (1920 m), the point was retained in the model.

Daily precipitation amounts at St Mary were multiplied by the modelled ratio of annual precipitation when calculating daily precipitation at any site. This assumes that daily precipitation mimics the pattern of average annual data, which will not necessarily be the case. Nevertheless, the precipitation model captures the essential features described by (Barrett *et al.*, 1991), namely precipitation increasing with increasing elevation and that the western side of the park is moister than the eastern side.

## 3.2 Lightning ignition model

*Introduction*

There has been numerous investigations into the distribution of lightning strike and lightning-caused fire at the global and (sub) continental scales (Flannigan & Wotton, 1991; Granstrom, 1993; Price & Rind, 1994), these scales are too coarse for prediction based on the finer-scale landscape structures that characterise ecological systems and management units. Studies on lightning strike distribution at this landscape level are relatively uncommon, but include those by Minko (1975), van Wagtendonk (1991), McRae (1992) and Renkin & Despain (1992).

A recently developed model (McRae, 1992) uses detrending techniques to remove large-scale trends in elevation in order to produce a meso-scale elevation residual surface. A meso-scale elevation residual is defined as the difference between the actual elevation of a site and the average elevation of its neighbourhood. McRae (1992) derived the average elevation of a site's neighbourhood (known as the macro-scale elevation of the site) using the average of all sites within a radius of 1750 metres. The meso-scale elevation residual was used to predict sites that are prone to lightning ignitions in the ACT. McRae (1992) found that lightning ignitions were more likely to occur nearer to the zero meso-scale elevation residual contour (or the line that joined points in the landscape that had a meso-scale elevation residual of zero) than was to be expected by chance. However, Cary (1998) reanalysed McRae's data and could not find such a relationship. Instead, Cary (1998) found an increasing likelihood of lightning-ignited fire with increasing macro-scale elevation and with increasing meso-scale elevation residual.

These finding coincides with what is known about processes, operating at quite different spatial scales, that affect the strike point of cloud-to-ground lightning. Firstly, and not surprisingly, there is a positive correlation between severe storm activity and lightning strike (eg. Reap & MacGorman, 1989). Given the orographic effect of mountain ranges, which can result in thunderstorms on the leeward side (Malan, 1963), it can be expected that increasing elevation associated with mountain ranges might be associated with increased probability of lightning strike.

However, this relationship may interact with meteorological and ecological gradients associated with increasing elevation, including temperature, moisture and fuel availability, resulting in a decline in the actual lightning ignitions over what might be expected at high elevation sites. van Wagtendonk (1986) proposed that while lightning strikes are common above 2,400 m elevation in Yosemite National Park, California, the burning and fuel conditions were less suitable for ignition and spread compared with lower elevation sites.

The second spatial scale which is fundamental for lightning strike location is one associated with the magnitude of the electrical potential over much smaller distances. Each lightning discharge, or flash, is characterized by a leader stroke which proceeds downward from the

cloud and is met by upward traveling streamers. The upward streamer that finally joins the leader stroke, and hence determines the point of fall of the stroke, is likely to start and develop most rapidly where the field strength is the greatest. These points include trees and upward projecting conductors (Chalmers, 1967), and presumably should include areas of the landscape that tend to project above their immediate surrounds, or areas that have a positive meso-scale elevation residual. For example, Vankat (1983) found that ignition was more likely on ridge-tops and less likely on valley floors than was to be expected by chance in Sequoia National Park, California.

This section examines these relationships for Glacier National Park to provide an empirical model for igniting fires in FIRESCAPE-GNP.

*Methods*

The USDA Forest Service provide locations of lightning ignitions in GNP since 1912 (Figure 13). Two surfaces were derived, using programs written in C programming language, from a 30 m DEM supplied by the USDA Forest Service, and covering a large area of GNP and its surrounds. Figure 14 presents the macro-scale elevation surface calculated for each pixels as the average elevation of all pixels in a 1750 m radius. Figure 15 presents the meso-scale elevation residual surface derived from subtracting the macro-scale elevation value from the actual elevation for each pixel.

Analyses were limited to pixels that were within the boundaries of GNP and were characterized by land cover other than water, barren, ice and snow. For both the macro-scale elevation and the meso-scale elevation residual surfaces, observed and expected lightning fire frequency distributions were developed. Observed distributions were determined from the number of lightning fires located in each bin range. Expected distributions were calculated from all of the available pixels in each bin range. Frequency distributions were converted to probability distributions for comparison for comparison.

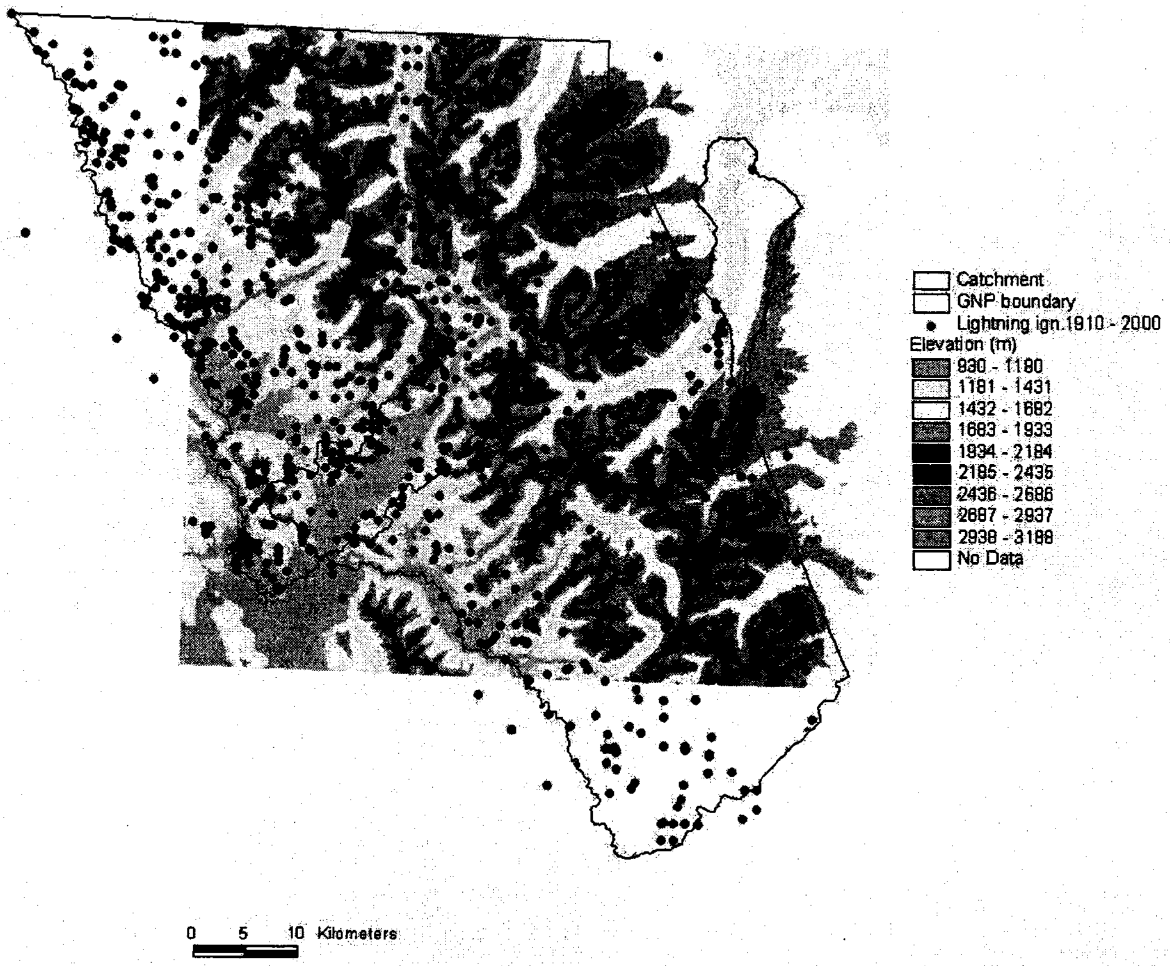


**Figure 13**. Location of lightning fires in Glacier National Park from the period (1912-2000). The boundaries of the Lake McDonald catchment (west) and St Mary catchment (East) are indicated in blue. The GNP boundary is indicated by the black line.

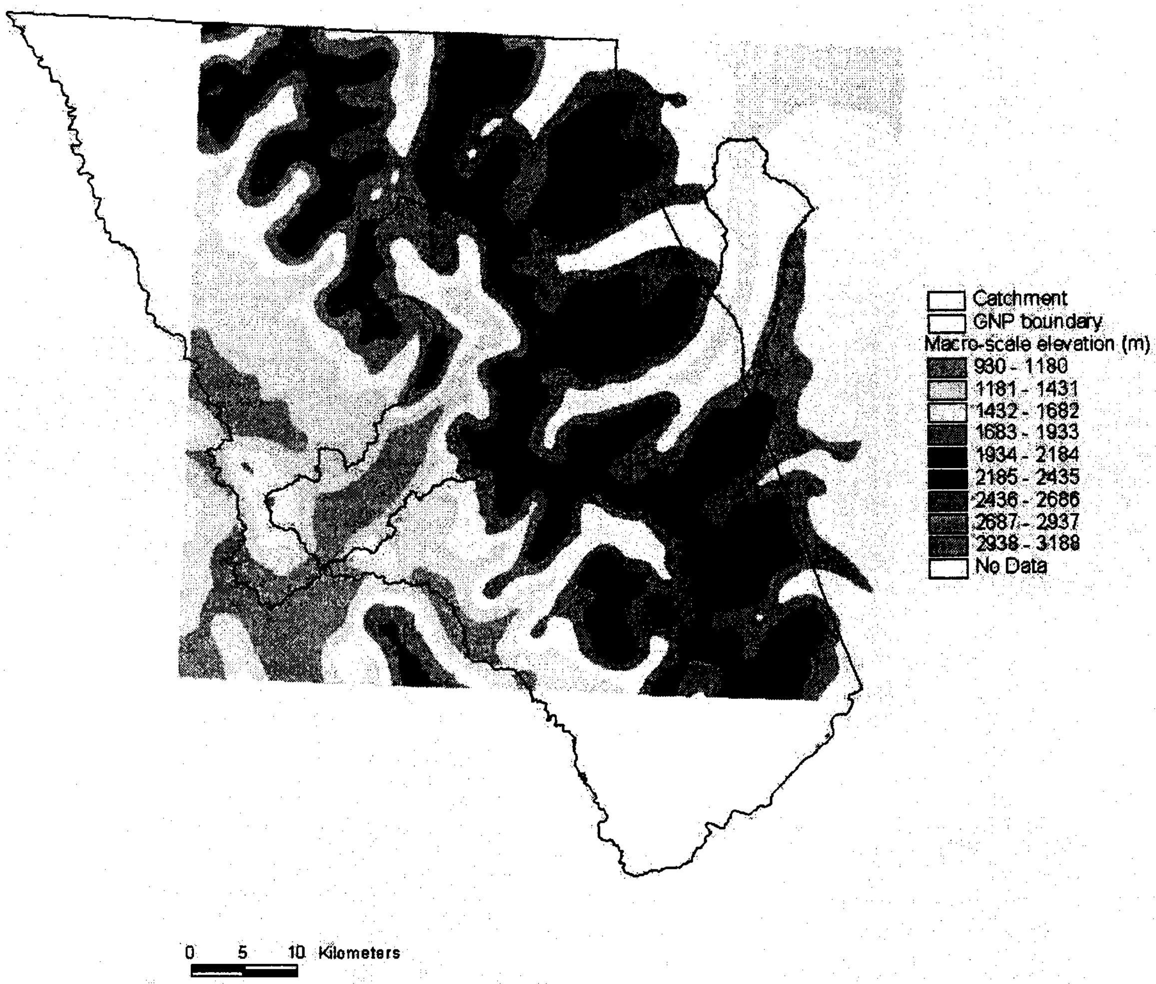


**Figure 14.** Macro-scale elevation for parts of Glacier National Park and surrounding region. The boundaries of the Lake McDonald catchment (west) and St Mary catchment (East) are indicated in blue. The GNP boundary is indicated by the black line.

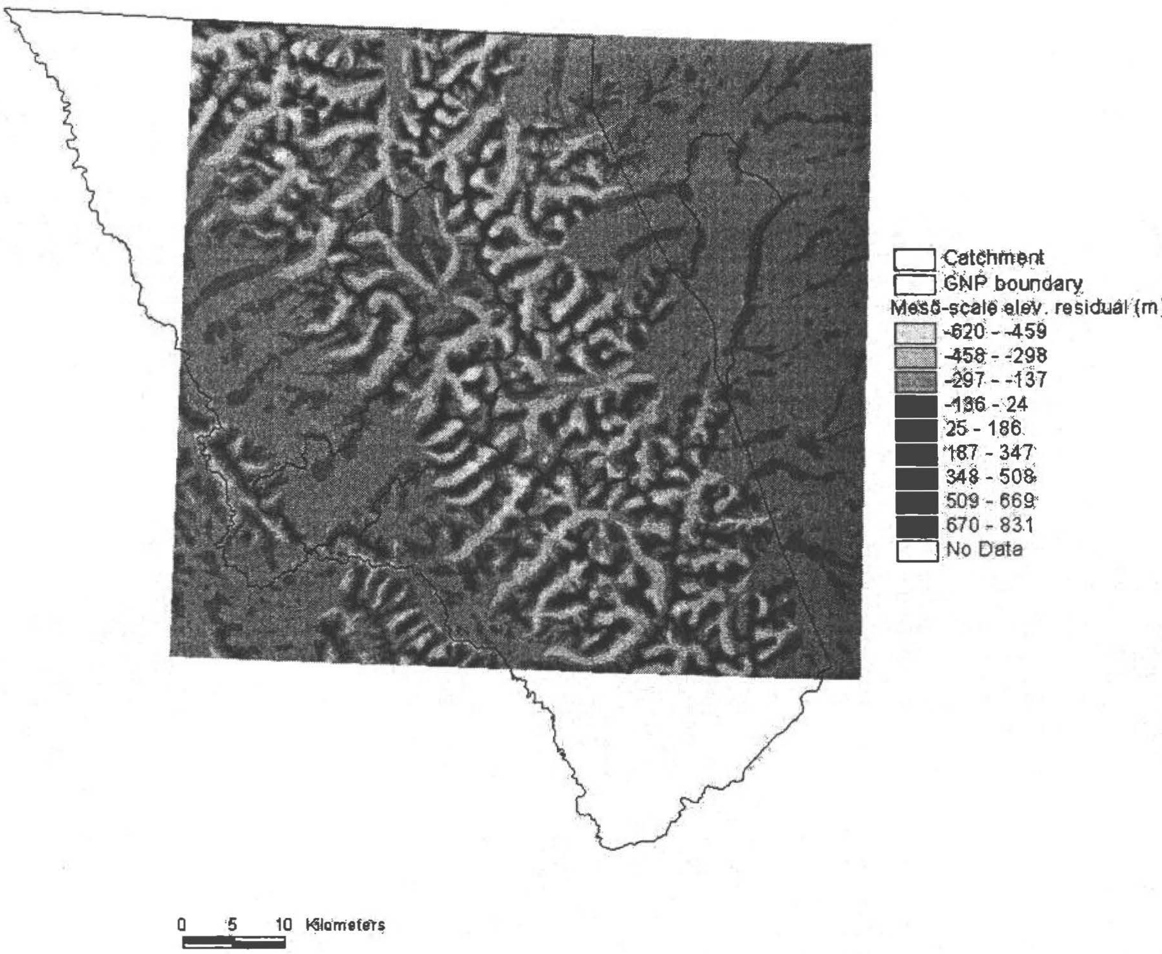


**Figure 15.** Meso-scale elevation residual for parts of Glacier National Park and surrounding region. The boundaries of the Lake McDonald catchment (west) and St Mary catchment (East) are indicated in blue. The GNP boundary is indicated by the black line.

*Results*

Lightning fires were more likely to occur at lower macro-scale elevations sites (Figure 16) conflicting with the expectation for the opposite result. These results agree somewhat with van Wagtendonk (1986) insofar as lightning ignitions occur less than would be expected by random chance as elevation increases. Lightning fires are more likely at point in the landscape which have a positive meso-scale elevation residual (Figure 17). This is in agreement with Vankat's (1983) study in California.

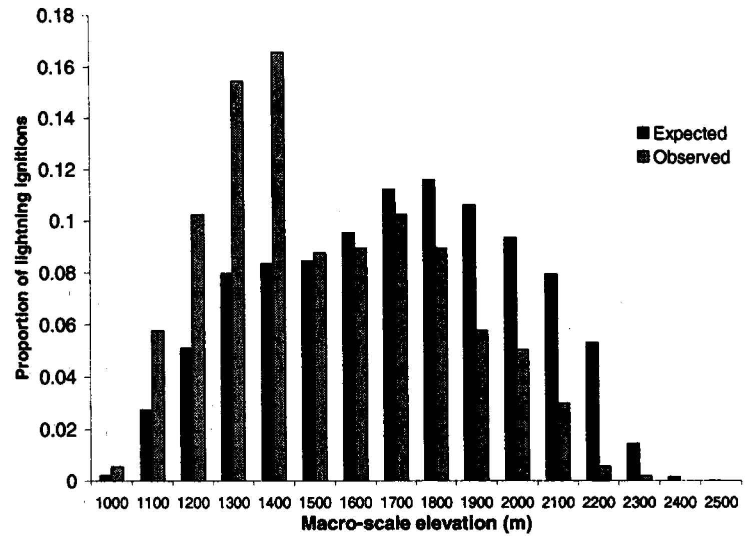


**Figure 16.** Observed and expected distribution of lightning ignitions by macro-scale elevation class in Glacier National Park, Montana.

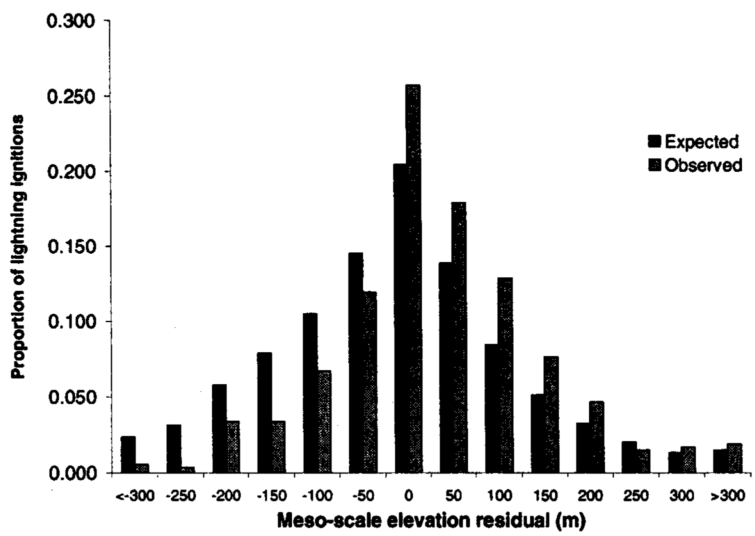


**Figure 17.** Observed and expected distribution of lightning ignitions by meso-scale elevation residual class in Glacier National Park, Montana.

*Discussion*

These results demonstrate relationships between landscape and ignition probability that can be explained by invoking and understanding of lightning behaviour and effects of elevation on fuel availability and fuel moisture regime. They have important implications for modelling of lightning ignition in Glacier National Park. Firstly, while there a greater likelihood of lightning-ignited fires at lower elevations, there is no evidence that lightning

*per se* is affected by the actual elevation. Lightning-ignited fires may be less common at higher elevations because of lower fuel amounts and higher fuel moisture. This conflicts with the findings of a similar study in the mountainous region of the Australian Capital Territory region, Australia, where lightning-ignited fires were more likely than expected at higher elevations (Cary, 1998; Cary and Banks, 1999). The maximum elevation in that study was around of 1700m, presumably meaning that fuel amount and condition was less limiting than in Glacier National Park. Given the result for Glacier National Park, it is assumed that lightning ignitions in FIRESCAPE-GNP are random with respect to actual site elevation.

However, the strong positive relationship between the occurrence of lightning ignited-fires and meso-scale elevation residual, as was observed for the ACT region (Cary, 1998; Cary and Banks, 1999), warrants distributing lightning-ignited fires in FIRESCAPE-GNP so that they mimic this relationship.

## 3.3 Fuel models

Unlike FIRE-BGC, FIRESCAPE has a simple empirical approach to modelling the amount of fuel available for combustion when a site burns. FIRE-BGC explicitly models trees and stands, and their succession, as they are subject to disturbance through time. Fuel production is a function of stand characteristics, although decomposition is comparatively deterministic. In FIRESCAPE, vegetation is not modeled. Instead, fuel amount is a simple function related to fuel age. FIRESCAPE-ACT incorporates the litter accumulation model of Olson (1963) which is based on rates of litter production and decomposition.

Parameters for the Olson (1963) litter model were not readily available for vegetation in Glacier National Park. Therefore, simple empirical fuel models for "fire groups" which represent categories based on vegetation composition, tree ecology and fire histories (Keane *et al.*, 1989). McArthur's (1967) fire spread algorithm has fine surface fuel (<6mm in one dimension) as its only fuel input. However, given the importance of 10-hour time lag fuel for fire behaviour in these systems, it was also included, along with 1-hour time lag fuels and litter. Similarly to Keane *et al.* (1989), duff does not contribute to fire behaviour.

Keane *et al.* (1989) provide parameters for woody fuel accumulation equations for the seven fire groups indicated in Figure 18. Litter could not be modeled using the approach of Keane *et al.* (1989) because rates of litter fall are not simulated in the model. Instead, a simple two-step litter accumulation model was parameterized so that resulting litter accumulation mimicked the litter curve in Figure 10f of Keane *et al.* (1989) (Figure 19). The same litter curve was used for all fire groups, although dynamics of 1–hour and 10-hour time lag fuels were modeled as for Keane *et al.* (1989).

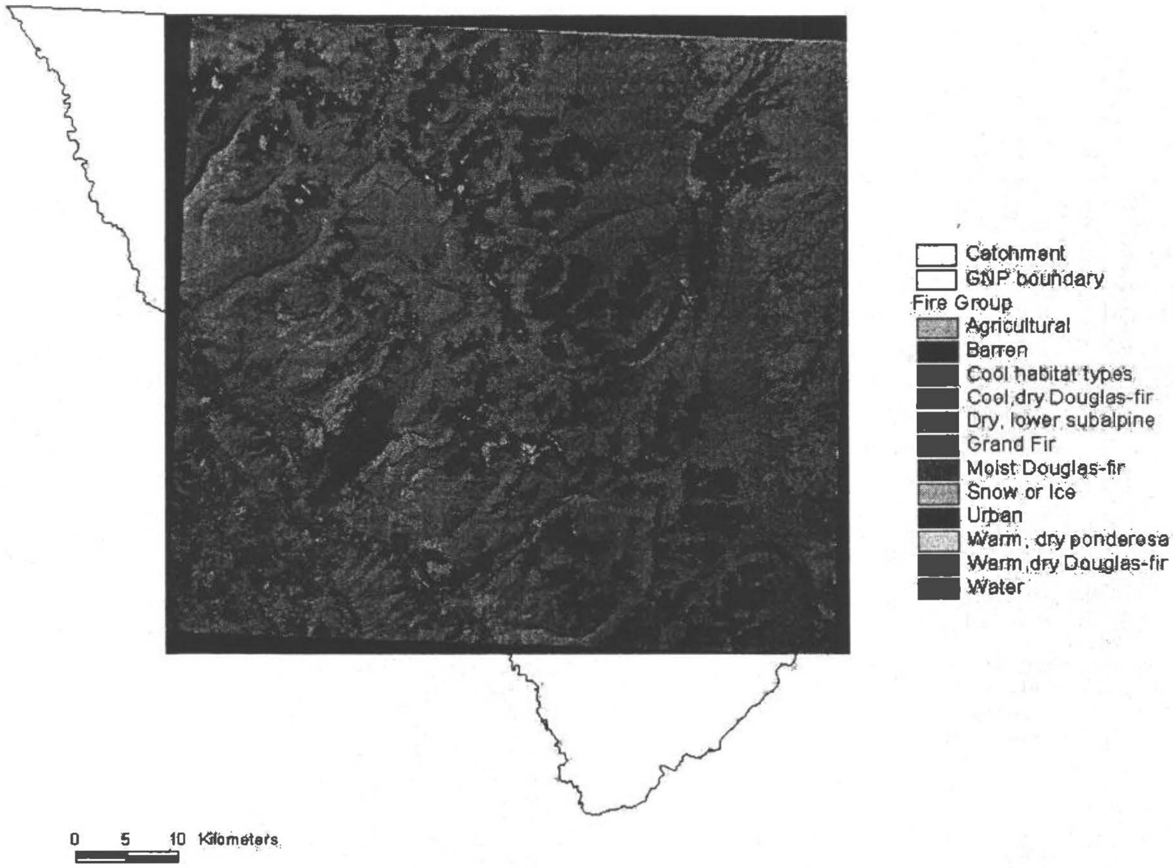


**Figure 18.** Distribution of sites by fire group (Keane *et al.*, 1989) in Glacier National Park, Montana, USA.

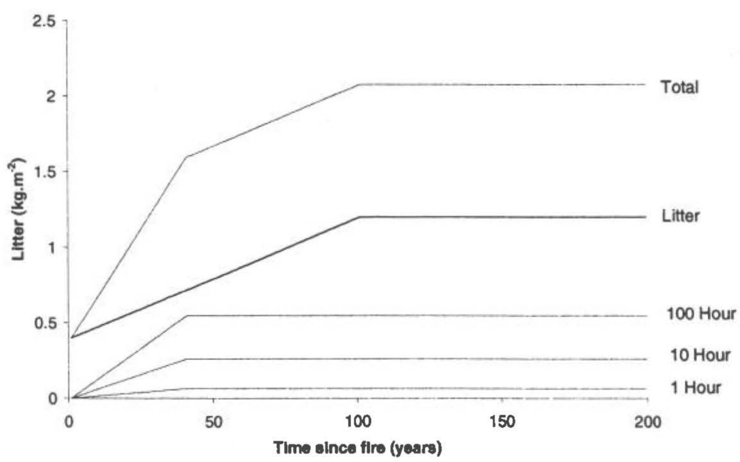


**Figure 19.** Fuel dynamics for Fire Group 3 (Warm, dry Douglas-fir) used in FIRESCAPE-GNP in Glacier National Park, Montana, USA.

### 3.4 Simulation of fire events

Ignition events are more likely on days with particular weather than others. Cary (1998) found for that in the Australian Capital Territory region, Australia, lightning is more likely in summer, followed by autumn, then spring and winter, and is more likely on wet days compared to dry days. Further, irrespective of the day, lightning was more likely as the maximum temperature of the day increased further above the mean maximum temperature for the month. Given that the ACT and GNP regions are somewhat similar in that summers are dominated by convective precipitation while frontal precipitation predominates in winter, the lightning probability functions for the ACT were used in the GNP study. If suitable meteorological data, including a record of thunder days or lightning occurrence, were available, the seasonal and weather-type patterns of lightning can be determined. Both data and time were limited in the implementation of this version of FIRESCAPE-GNP.

The model simulates daily weather variables for St Mary using the stochastic weather generator described above. When a lightning ignition day is simulated, the location of the ignitions is determined by the lightning-location model described above. The number of lightning ignitions on any particular lightning day is rarely ever known with any confidence and the first sensitivity analysis conducted, once the model was completed, was into the effect of number of ignitions attempted per lightning day on the resulting fire regime.

Whenever a pixel is ignited, irrespective of whether by lightning or by an advancing fire front, FIRESCAPE-GNP determines the rate of spread from the ignition pixel to its immediate neighbours using McArthur's (1967) fire spread algorithm and the elliptical fire spread model of Van Wagner (1969). McArthur's (1967) algorithm includes the effects of short-distance spotting on forward rate of spread but FIRESCAPE does not incorporate long-distance spotting .To do so would require relatively trivial modification to the model, however, sufficient knowledge on numbers and distributions of long-distance spotting events is virtually absent in all fire-prone vegetation types.

For simplicity, the spread of fires is modelled on the same system of grid cells as the other data required by the model. The fire line propagates by moving from one fixed point to another fixed point after the appropriate amount of time has elapsed.

Head fire rate of spread is determined for each individual burning cell using the equation form of McArthur's Forest Fire Danger Meter (McArthur 1967; Noble *et al.*, 1980). Headfire rate of spread ($R_H$) is given by

$$R_H = 0.0012 \times FFDI \times W \qquad \text{Equation 7}$$

where FFDI is the Forest Fire Danger Index and W is fuel load (tones.ha$^{-1}$) and is adjusted to take into account the slope $\beta$ (degrees) in the direction of fire spread according to (Noble *et al.*, 1980)

$$R_{HS} = R_H \times e^{(0.069 \times \beta)}$$ Equation 8

The equation for the FFDI is (Noble *et al.*, 1980)

$$FFDI = 2.0 \times e^{(-0.045 + 0.987 \times \ln(D) - 0.0345 \times H + 0.0338 \times T + 0.0234 \times V)}$$ Equation 9

where:- $D$ is the drought factor; $H$ is the relative humidity (%); $T$ is the air temperature (°C); and $V$ is the average wind velocity in the open at a height of 10m ($km.hr^{-1}$).

The variables required (hourly meteorology, fuel load and drought factor) are calculated for individual cells as required. The drought factor combines information on short-term rainfall patterns with longer-term dryness from the Soil Dryness Index (SDI) (Mount 1972), an Australian derivation of the Keetch-Byram Drought Index (Keetch and Byram, 1968). The SDI for a burning pixel is back-calculated using stored modelled daily maximum temperature and precipitation which is extrapolated to the site of interest using the temperature lapse equations and the precipitation extrapolation equation described above.

Backfire rates of spread and length to breadth ratio are calculated in FIRESCAPE using the approach from the Canadian Forest Fire Behaviour Prediction System (CFFBPS). The backfire ROS model was developed using a function based on informal experience and limited data (Forestry Canada, 1992). It is adopted in FIRESCAPE given the lack of other approaches and studies that are amenable to the predominantly empirical nature of the Australian fire behaviour prediction systems. The rate of spread of the backfire is calculated as for head fire ROS except that when calculating the 'effective *Forest Fire Danger Index*' for the backfire, the wind term ($V$) is replaced by the effective windspeed for the backfire ($V_{BACK}$) ($km.hr^{-1}$) where

$$V_{BACK} = V \times e^{(-0.05039 \times V)}$$ Equation 10

where V is the ambient windspeed.

The length to breadth ratio($L_B$), or the eccentricity, of the ellipse describing the shape of a fire has a significant positive correlation with windspeed (Green *et al.*, 1983). The CFFBPS (Forestry Canada, 1992) uses an empirical relationship between $L_B$ and $V$ for forest fires which takes the form

$$L_B = 1.0 + 8.729 \times \left(1 - e^{-0.030 \times V}\right)^{2.155} \qquad \text{Equation 10}$$

and is the only empirical relationship that was constructed principally for standing timber fuel types.

Fires spread from pixel to pixel, provided they are sufficiently intense to maintain propogation. An attempt to spread from a pixel to one of its neighbours will be unsuccessful if the calculated Byram Fireline Intensity (Byrm, 1959) is less than 83 $kW.m^{-1}$ (Cary, 1998). This value was calculated as the fireline intensity that would be achieved using rate of spread from McArthur's (1967) fire spread algorithm assuming an FFDI of one (conditions where fires are virtually self-extinguishing) and a standard fuel load of 12.5 $tonnes.ha^{-1}$. However, it is possible that a very low intensity fire will burn in a cell with a rate of spread that does not warrant spreading it to the next cell. The fire cannot be extinguished because it represents an important ignition source should the conditions change so that more intense fire behaviour can develop. Also, the fire cannot be spread because the time-to-ignition of its neighbours is so long (perhaps days) that it is likely that conditions will change, perhaps resulting in extinguishment. For this reason, a lower limit is placed on the intensity at which a fire will spread to its neighbours, as opposed to the intensity below which a fire will be extinguished. For the initial configuration of FIRESCAPE, this value was set at 100 $kW.m^{-1}$, approximately 20% more intense than the intensity of extinguishment but below the recommended intensity of 150 required for a satisfactory prescribed burn (Vines, 1981). A fire extinguishes when there are not successful spread events. This usually occurs because of a fire-event ending rain event. Further, it is possible for a fire to continue spreading in one direction (e.g. upslope or downwind), but not propagate in the other (e.g. down slope, or upwind).

Given this approach, once fires are ignited, they spread across the landscape being influenced by patterns of slope, fuel, and diurnal variation in meteorological conditions including windspeed. Fire events are superimposed to develop a fire regime. Outputs include the number of fire per pixel, the average inter-fire interval per pixel, the average fireline intensity per pixel, and the distribution of fire events encountered by a pixel by season.

## 4. Calibration

The single greatest uncertainty in FIRESCAPE is the number of lightning ignition attempts that should be made on any one ignition day. The only possible approach to determining this is by varying the probability of attempted lightning ignitions per day which is conducive to the phenomena, and compare resulting patterns of fire occurrence to what is know about real fire history in the study area. Barrett *et al.* (1991) studied the fire frequency

in different parts of western Glacier National Park. They identified two kinds of primeval fire regimes that are directly comparable to FIRESCAPE results because there is no anthropogenic effects in the modelling approach. These regimes were a mixed-severity fire regime at mean intervals of 25-75 years in areas with drier climate and gentler terrain (e.g. North Fork Flathead valley) and a regime of infrequent stand-replacing fires at mean intervals of 140-340 years for wetter areas with more rugged terrain (e.g. McDonald Creek-Apgar Mountains and Middle Fork Flathead areas). Of these, only the McDonald Creek – Apgar mountains area is fully part of this study. The landscape modelled does cover parts of the other areas but given the extensive edge-effects known to occur with this modeling approach, they are not likely to properly represent the fire regimes that would be predicted if it were not for edge-effects.

The probability of an attempted lightning ignition made on any one ignition day was varied between one and 1/32 (0.03125) by sequentially halving the probability for each new model run (1, 0.5, 0.25, 0.125, 0.0625, 0.03125). The average number of fires occurring per pixel in the Lake McDonald and St Mary catchment were determined from 1000 year simulations. Fires were allowed to burn in the first 100 years of the simulation but not recorded in an attempt to generate realistic spatial patterns of fuel age before recording of fires commenced. The relationship between probability of an attempted lightning ignition made on any one day conducive to lightning (Figure 20) indicate a curve-linear relationship. Averages of the number of fires per pixel was selected for analysis since some pixels do not experience many fires, especially when the probability of an attempted lightning ignition is low, and therefore difficult to calculate an inter-fire interval. To coincide with fire frequencies of 140 to 340 years (average 217) in the Lake McDonald cathcment (Barrett *et al.*, 1991), the average number of fires would be in the order of three to seven. Figure 20 indicates that a relatively low inter-fire interval, say around 0.0625, is an appropriate value for this variable. The average number of fires in the St Mary catchment is less than for Lake McDonald, irrespective of the ignition probability. This is likely a function of comparatively higher elevation and a greater proportion of barren landscapes in the St Mary catchment. However, it is likely that the interval between fires would be shorter (i.e. greater number of fires) for the St Mary catchment (R. Keane *pers comm.*) indicating that FIRESCAPE-GNP does not include all the important processes determining spatial variation in fire regimes.

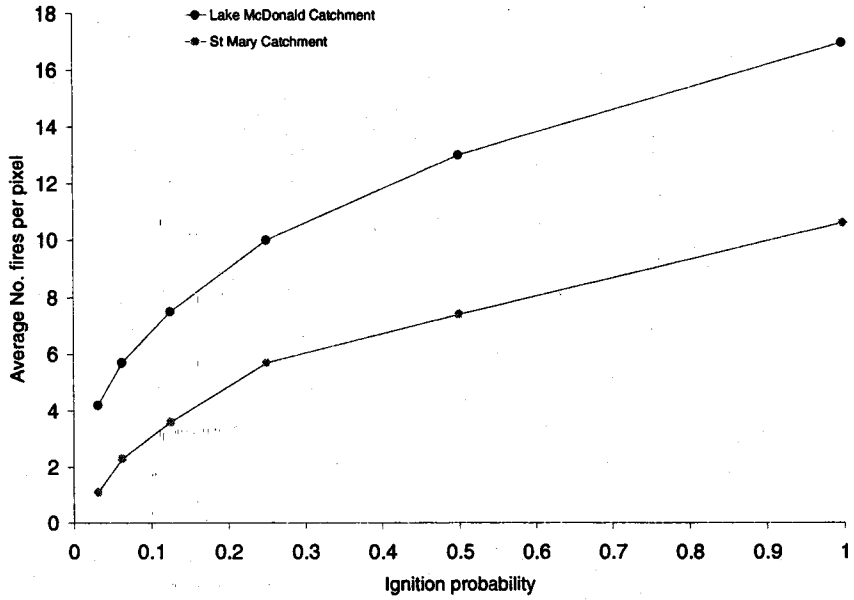


**Figure 20.** Effect of the probability of an attempted lightning-ignition (per day conducive to lightning ignition) on the average number of number of fires per pixel for the Lake McDonald cathcment and the St Mary catchment in Glacier National Park, Montana, USA.

Assuming a probability of ignition on days conducive to lightning of 0.0625, fire regimes in GNP were simulated for 1500 years using FIRESCAPE-GNP and the average inter-fire interval was calculated for the lake McDonald and the St Mary catchment as 468 and 899 years respectively. These values were reached assuming that the average inter-fire interval for sites that did not record any fire, or only one fire, was 1500 years given that an inter-fire interval cannot be calculated from less than two fires. The value for the Lake McDonald catchment is too high when compared to the data of Barrett *et al.* (1991). The igniton probability value was doubled to 0.125 and the average inter-fire interval was calculated for the lake McDonald and the St Mary catchment as 173 and 450 respectively. More importantly, a considerably greater proportion of the catchments experienced at least two fires, representing a more realistic outcome. These values are in closer agreement with Barrett *et al.* (1991) for the Lake McDonald catchment and this ignition value was used for the remaining simulations.

**5. Results**

Figure 21 (a – c) presents three examples of the number of fires over 100 years as simulated by the calibrated version of FIRESCAPE-GNP. Most of the landscape burnt in each

simulation is by large fires, which are of the same order of size as the recent large fires that occurred in the study are (Figure 22), although as commonly observed in a real systems, there is a greater number of smaller fires.

Average inter-fire interval, average fireline intensity and average number of fires per pixel by season is presented in Figure 23 (a – d).

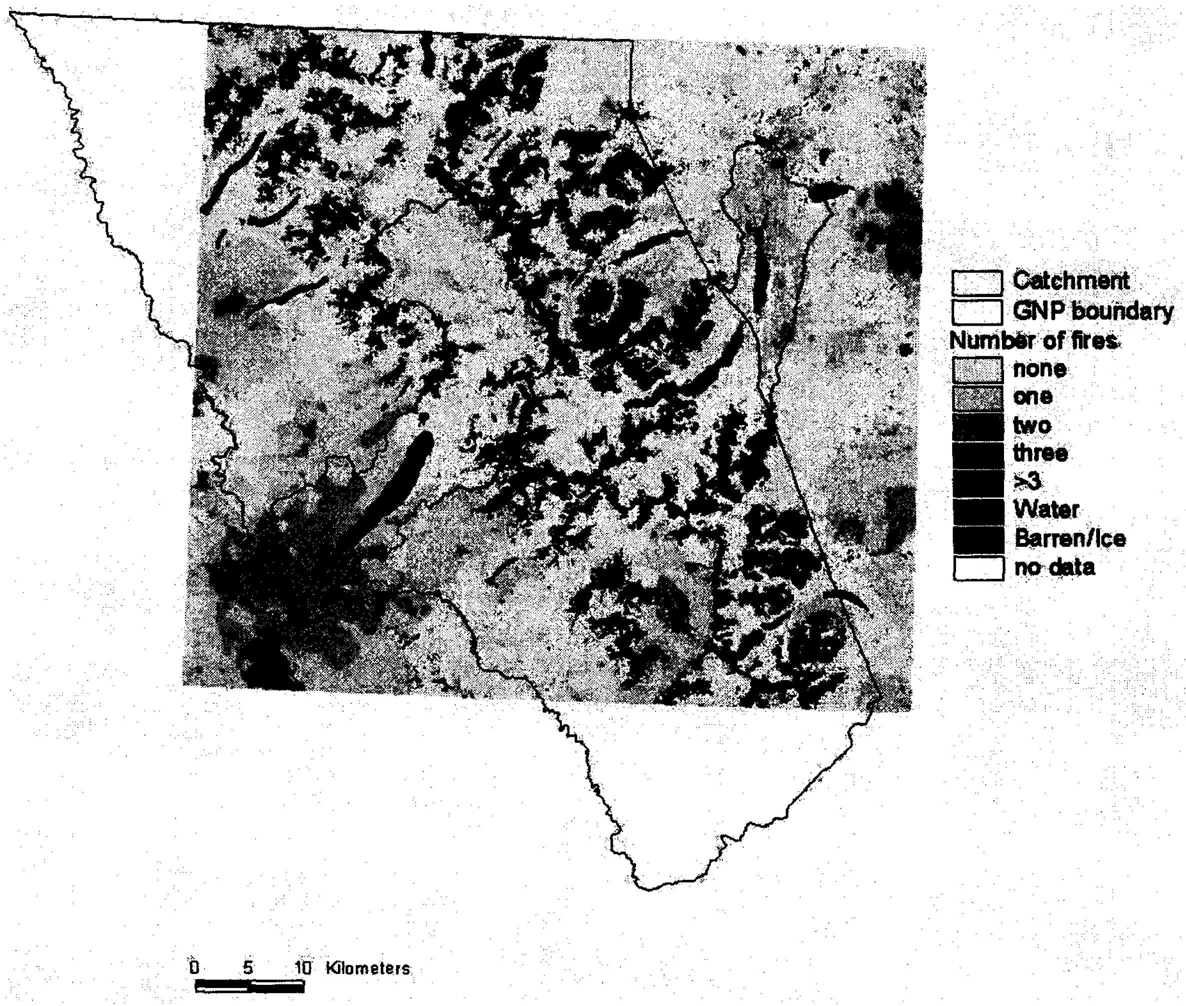


**Figure 21a.** Number of fires over 100 years (replicate a) simulated by FIRESCAPE-GNP in Glacier National Park, Montana, USA.

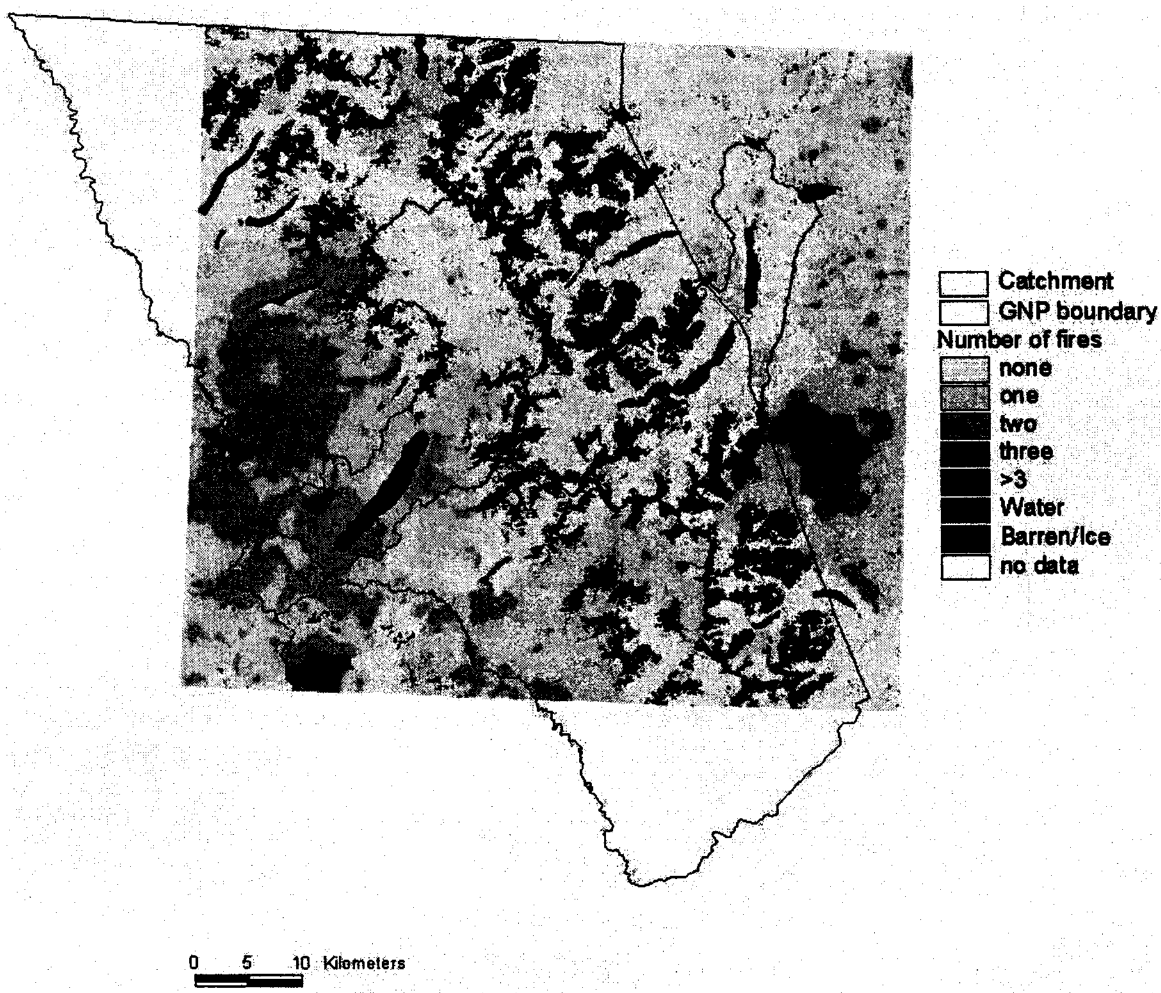


**Figure 21b.** Number of fires over 100 years (replicate b) simulated by FIRESCAPE-GNP in Glacier National Park, Montana, USA.

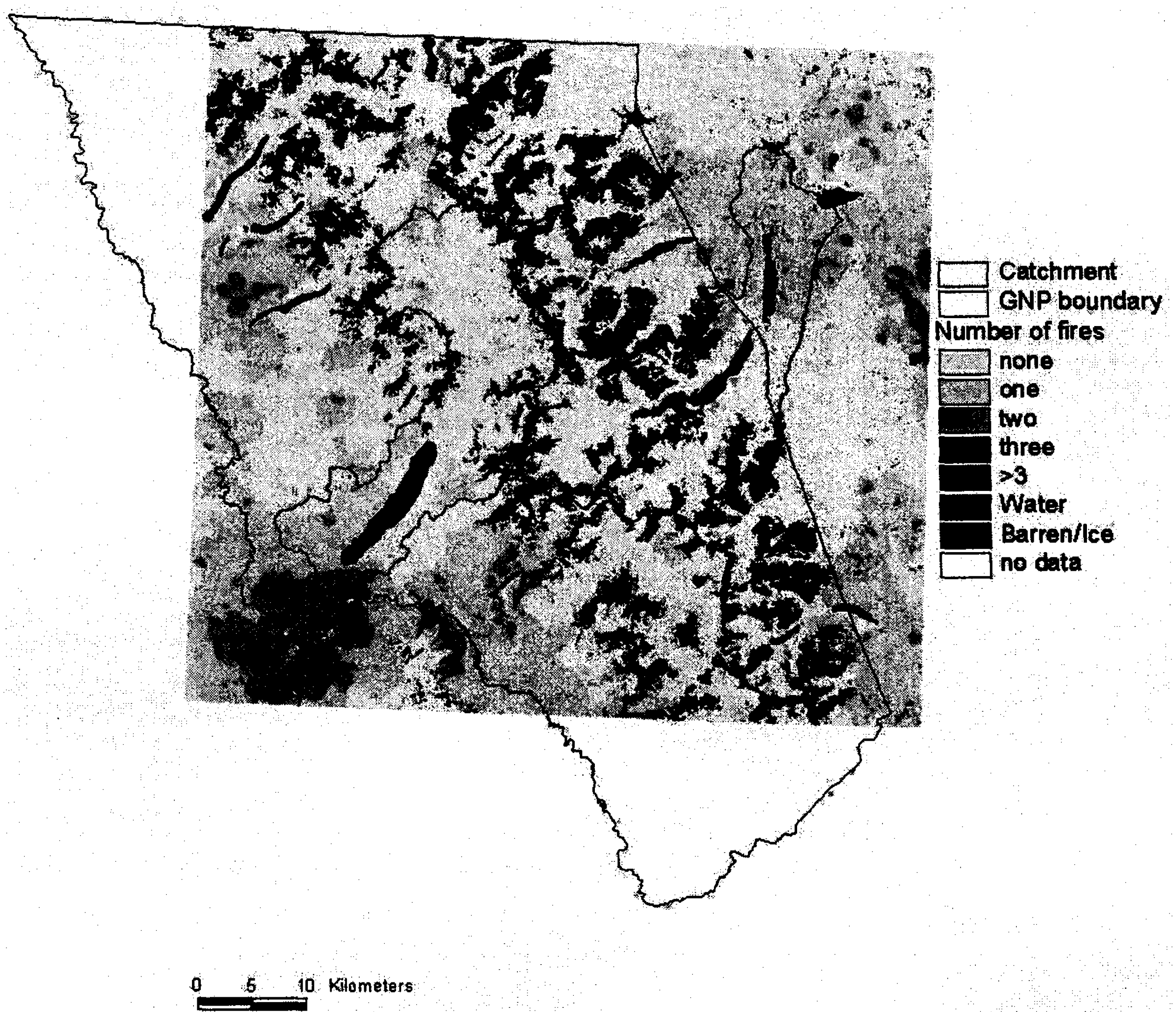


**Figure 21c.** Number of fires over 100 years (replicate c) simulated by FIRESCAPE-GNP in Glacier National Park, Montana, USA.

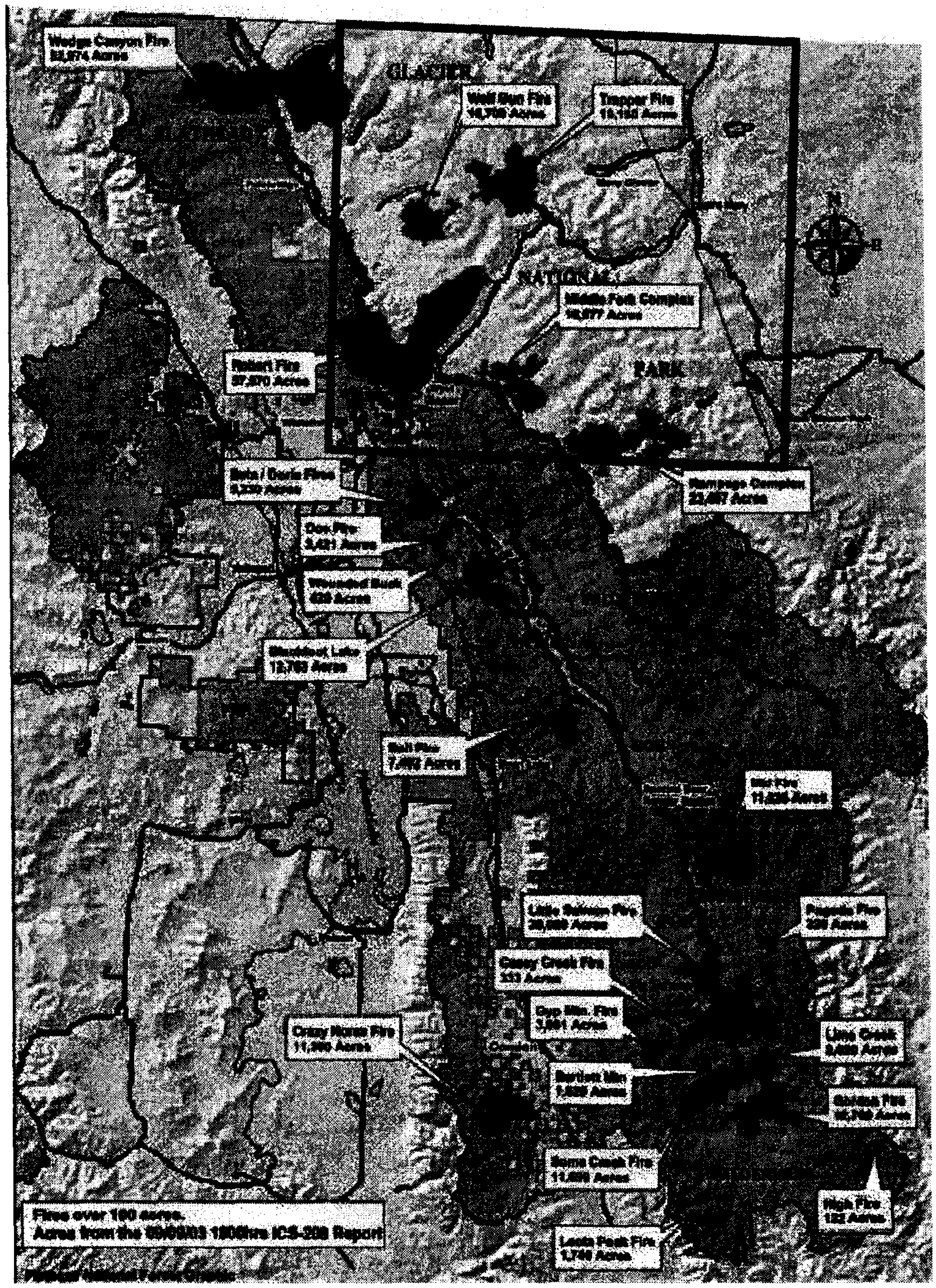


**Figure 22.** Areas burned by fire in GNP, Flathead National Forest and Bob Marshall Wilderness, Montana, USA, up to the 10th of September, 2003. (Source: Glacier National Park / Flathead National Forest Fire Information webpage - http://www.fs.fed.us/nwacfire/ . Boundaries of the current study is indicated by blue box.

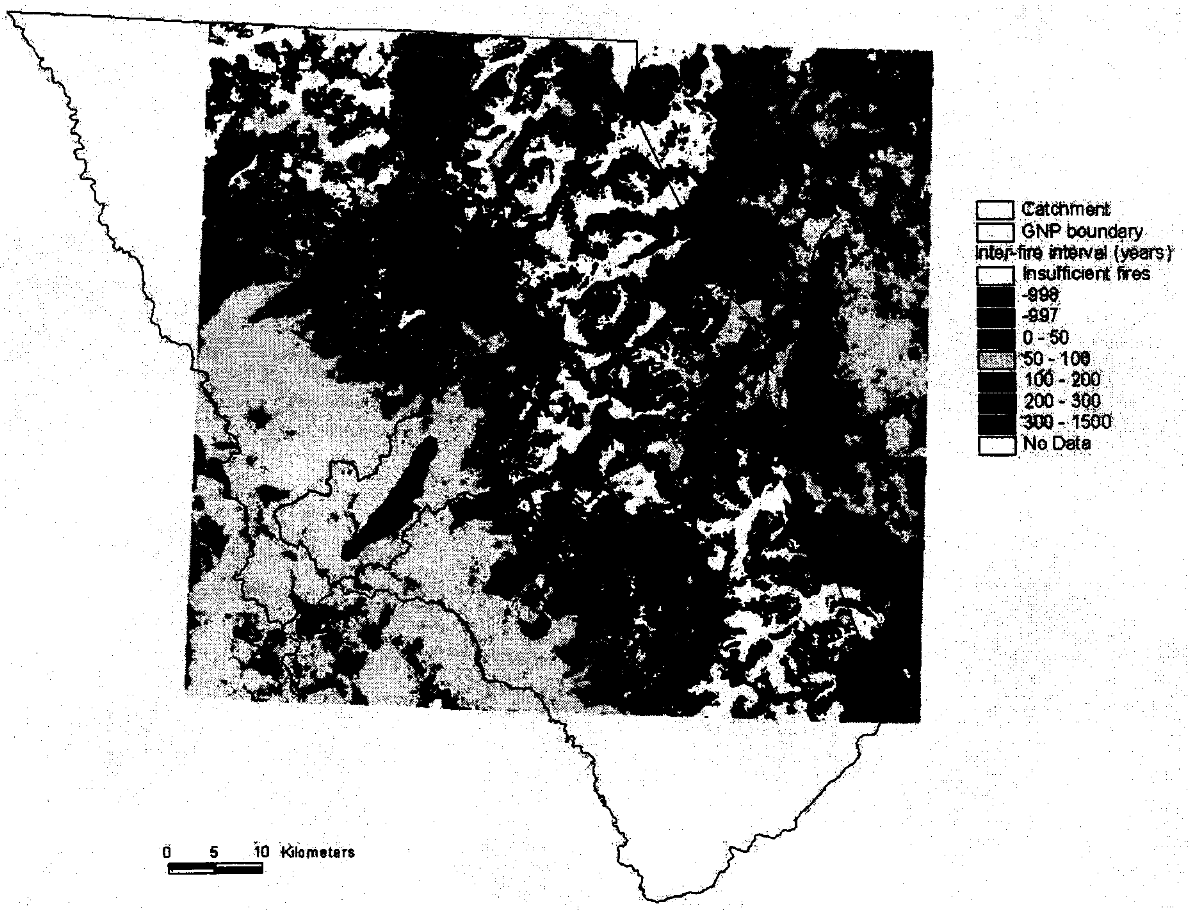


Figure 23a. Average inter-fire interval (years) from a 1500 year FIRESCAPE-GNP simulation in Glacier National Park, Montana.

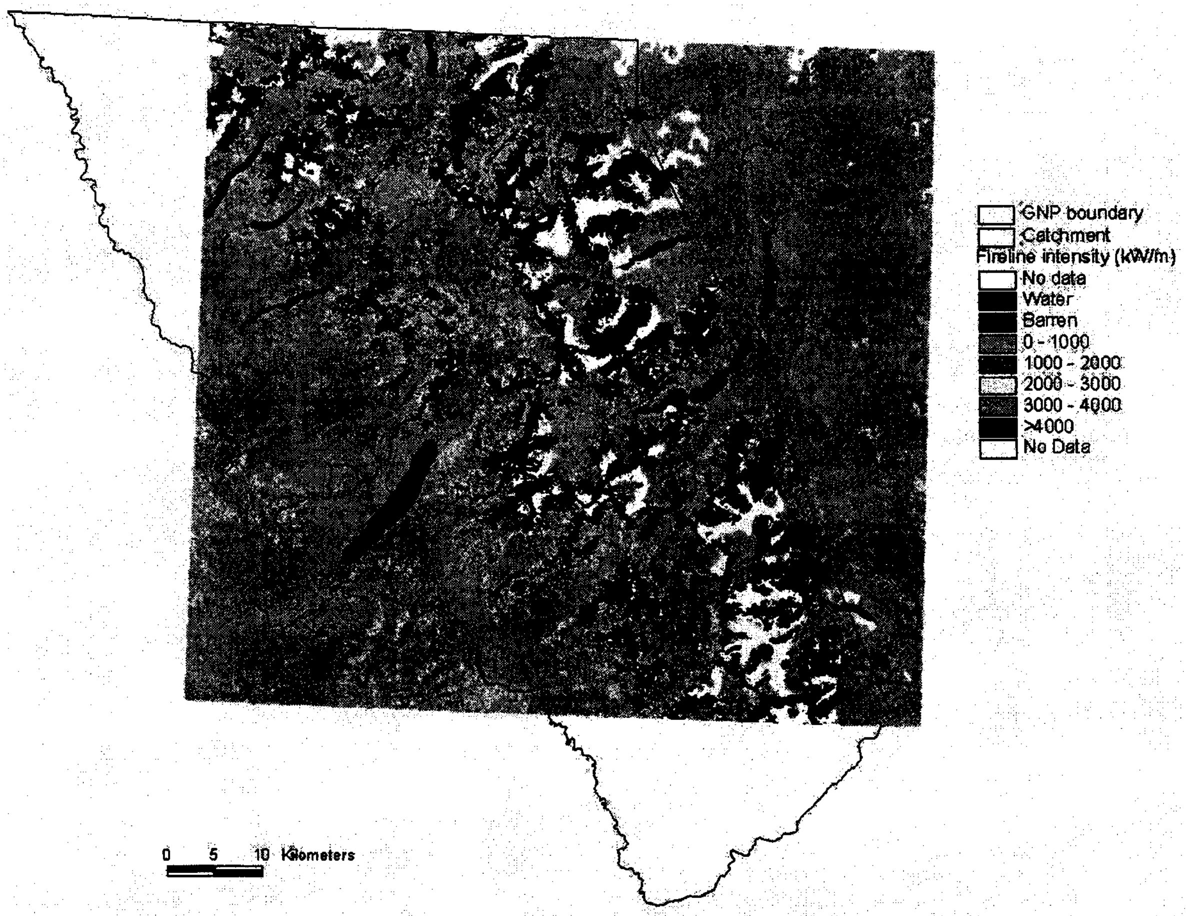


Figure 23b. Average Fireline intensity ($kW.m^{-1}$) from a 1500 year FIRESCAPE-GNP simulation in Glacier National Park, Montana.

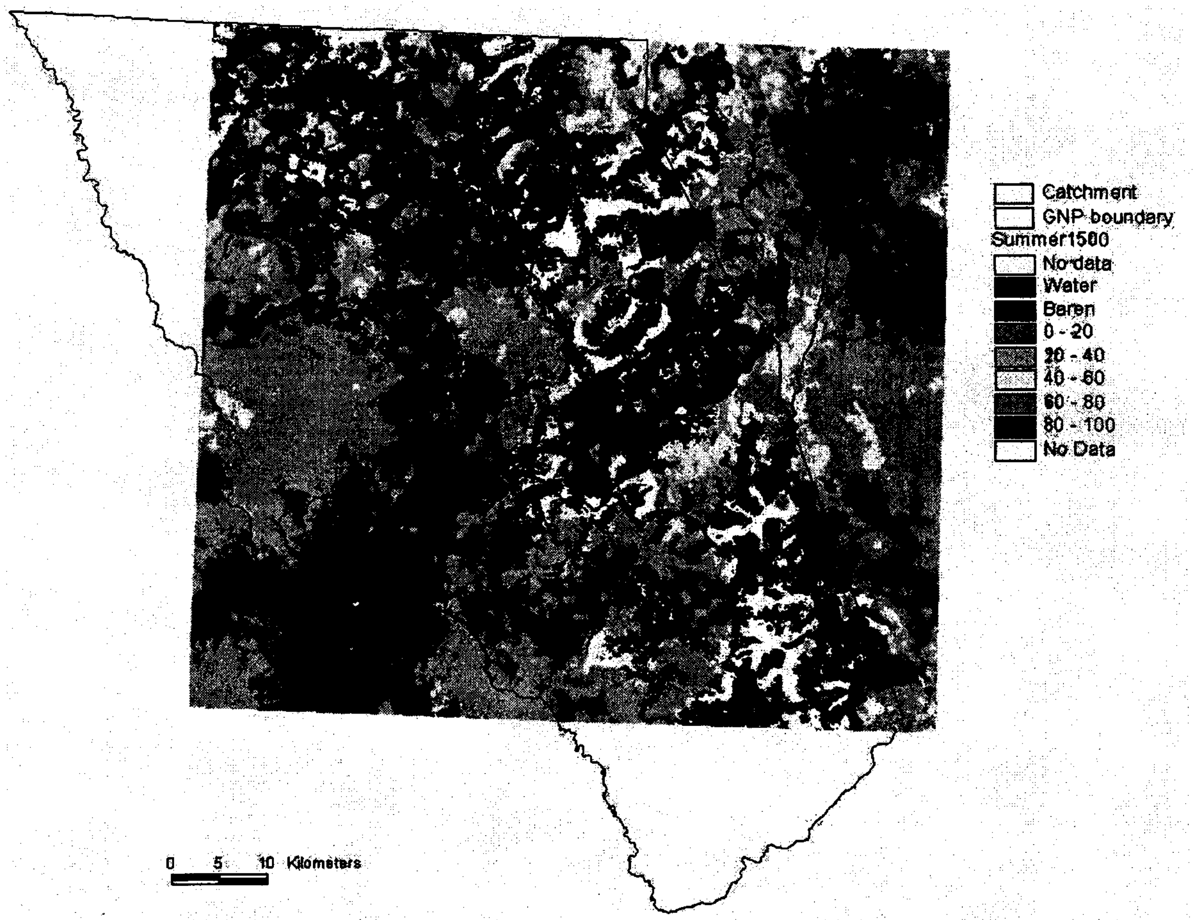


Figure 23c. Average percent of fires in summer from a 1500 year FIRESCAPE-GNP simulation in Glacier National Park, Montana.

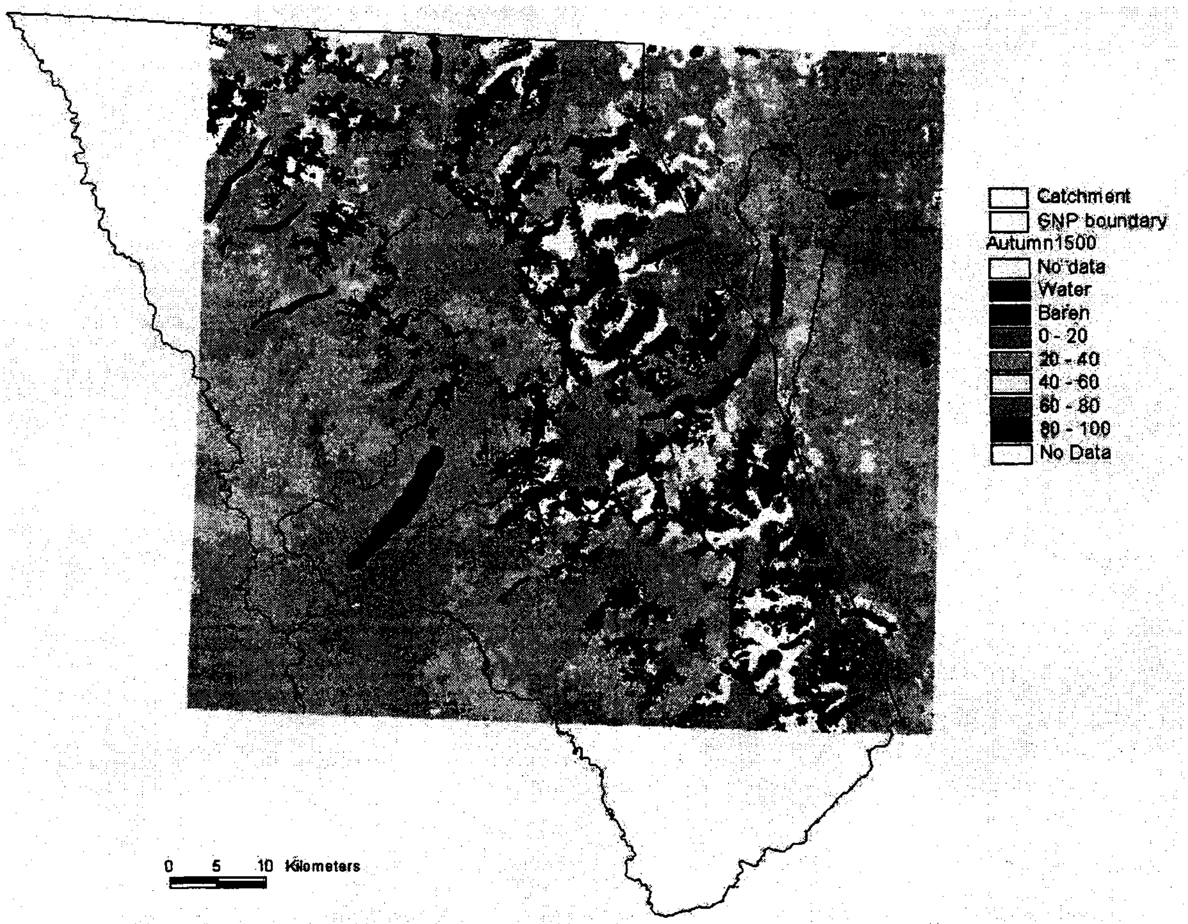


Figure 23d. Average percent of fires in autumn from a 1500 year FIRESCAPE-GNP simulation in Glacier National Park, Montana.

**Example of application**

Cary (2002) generated fire regimes for the Australian Capital Territory region in south eastern Australia using FIRESCAPE-ACT and climate change scenarios from the Commonwealth Science and Industry Research Organisation (CSIRO, 1996). An increase in temperature, reduction in relative humidity and a decrease in rainfall in the middle and latter part of the fire season resulted in a marked decrease in the interval between fires and an increase in the number of fires burning in autumn.

Hall and Fagre (2003) modelled glacier retreat and changes to vegetation distribution in the Blackfoot–Jackson Glacier Basin of Glacier National Park. They assumed a two to three degree celcius increase in temperature and a ten percent increase in precipitation by 2050 under 2 x $CO_2$ climate. FIRESCAPE-GNP was run assuming a three degree celcius increase in temperature and a ten percent increase in precipitation.

The increase in precipitation was simulated by increasing daily precipitation values by ten percent. This will affect fire danger directly as an input variable but also indirectly via the increased accumulated soil moisture in the soil dryness index, also an input into the fire danger index. Daily maximum and minimum temperatures were increased by three degrees celcius. This will affect fire danger directly as an input variable, but will also result in lower relative humidity and increased evaporation and consequently decreased soil moisture. Temperature and precipitation also affect the probability of an ignition day. However, this impact was not included in this experiment, resulting in the same number of ignitions as for the simulations presented in the results section. It is worth noting that Goldammer and Price (1998) predicted that lightning frequency would increase over continental areas with doubling of $CO_2$ and these increase can be incorporated in the model if it was warranted.

Hall and Fagre (2003) predicted that under particular scenarios of global warming, considerable areas of glaciers would disappear and that herbaceous and forest vegetation would invade the formerly barren areas. Given the importance of fuel to fire behaviour, and subsequently fire regimes, this change would likely have significant effects on fire regimes, however this affect has not been included since FIRESCAPE_GNP does not contain a dynamic vegetation model.

Figure 24a-c presents the modelled average inter-fire interval and percent of fires in summer and autumn across Glacier National Park assuming the conditions described above. A considerable decrease in the interval between fires is predicted. Changes in the percent of fires by season is smaller.

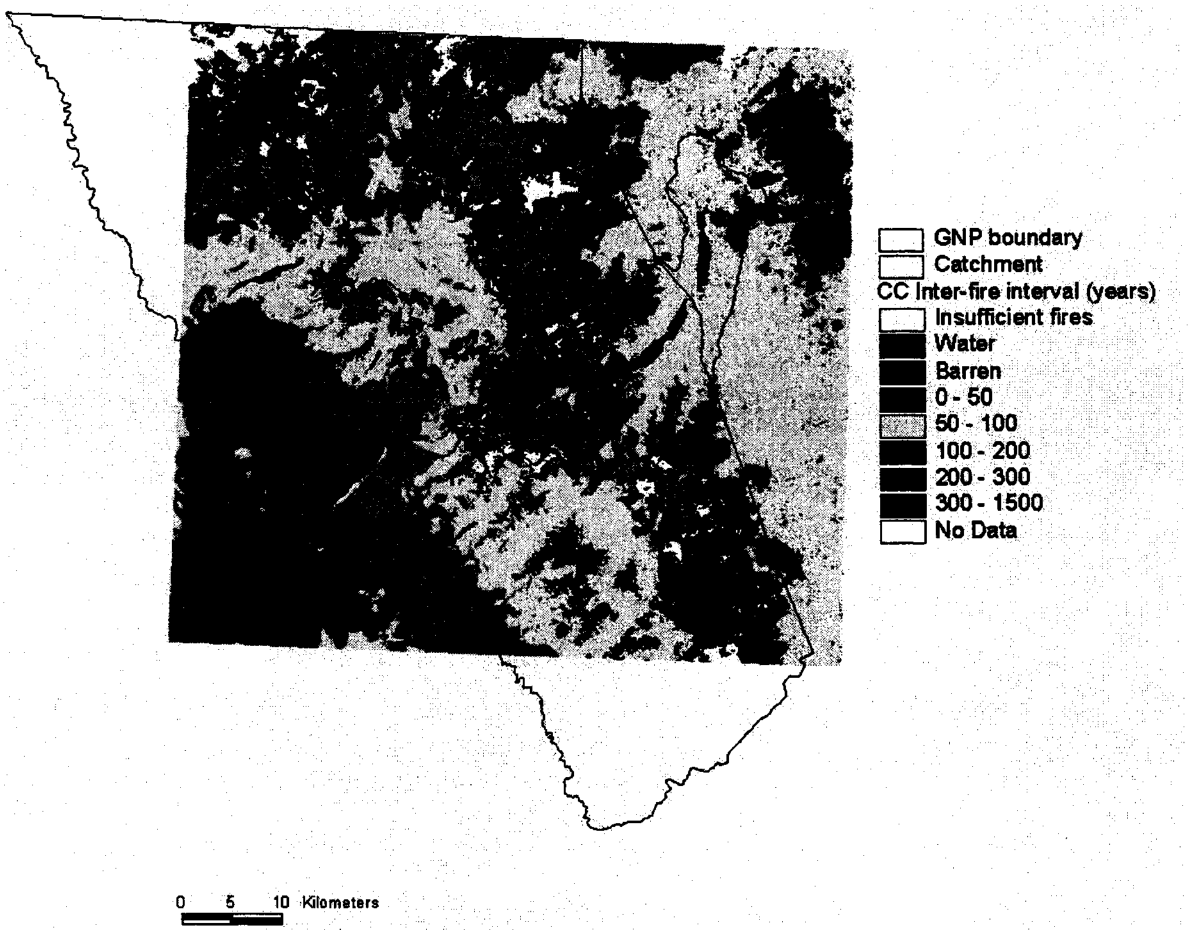


Figure 24b. Average inter-fire interval assuming climate change.

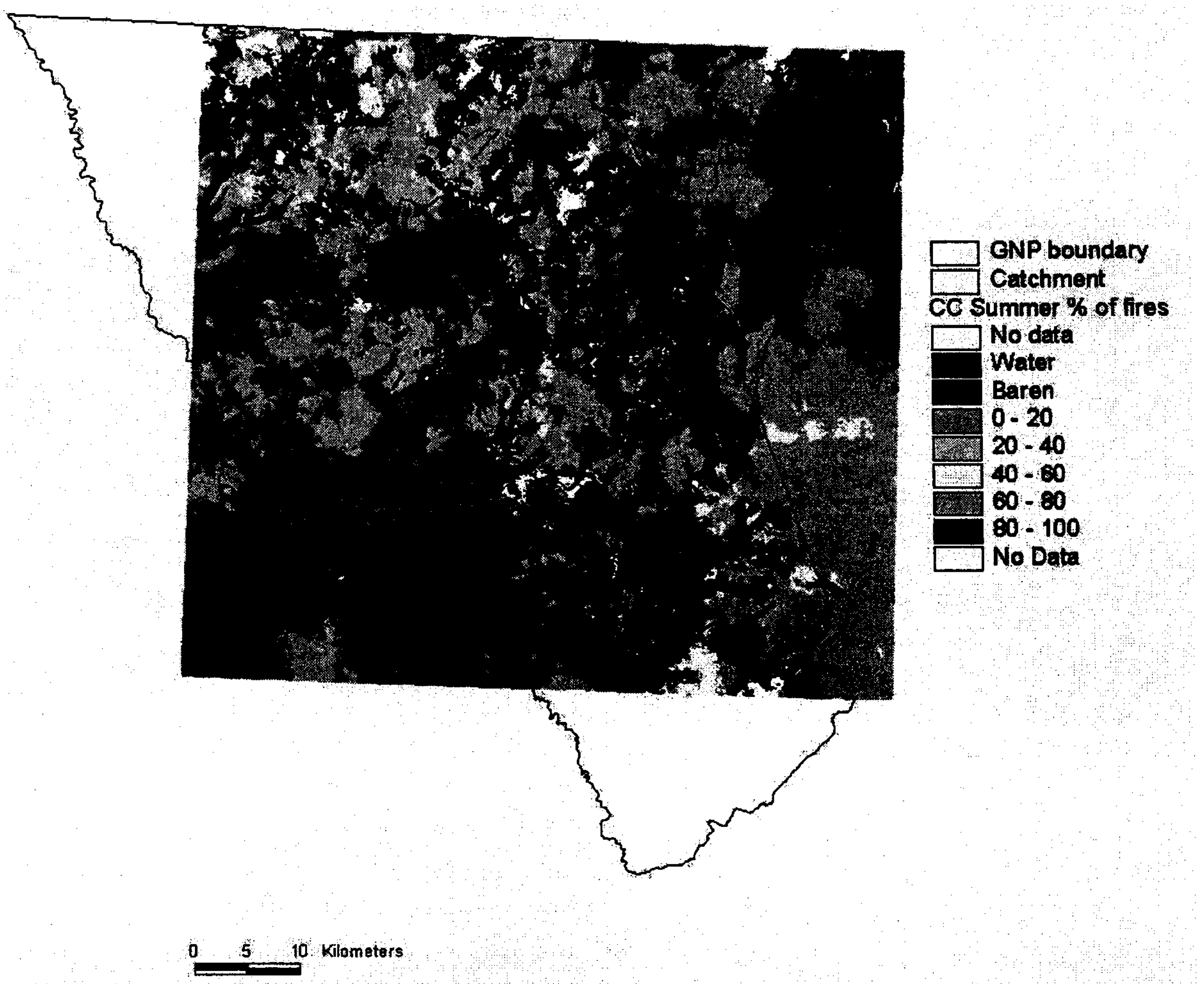


Figure 24b. Average percent of fires in summer assuming climate change.

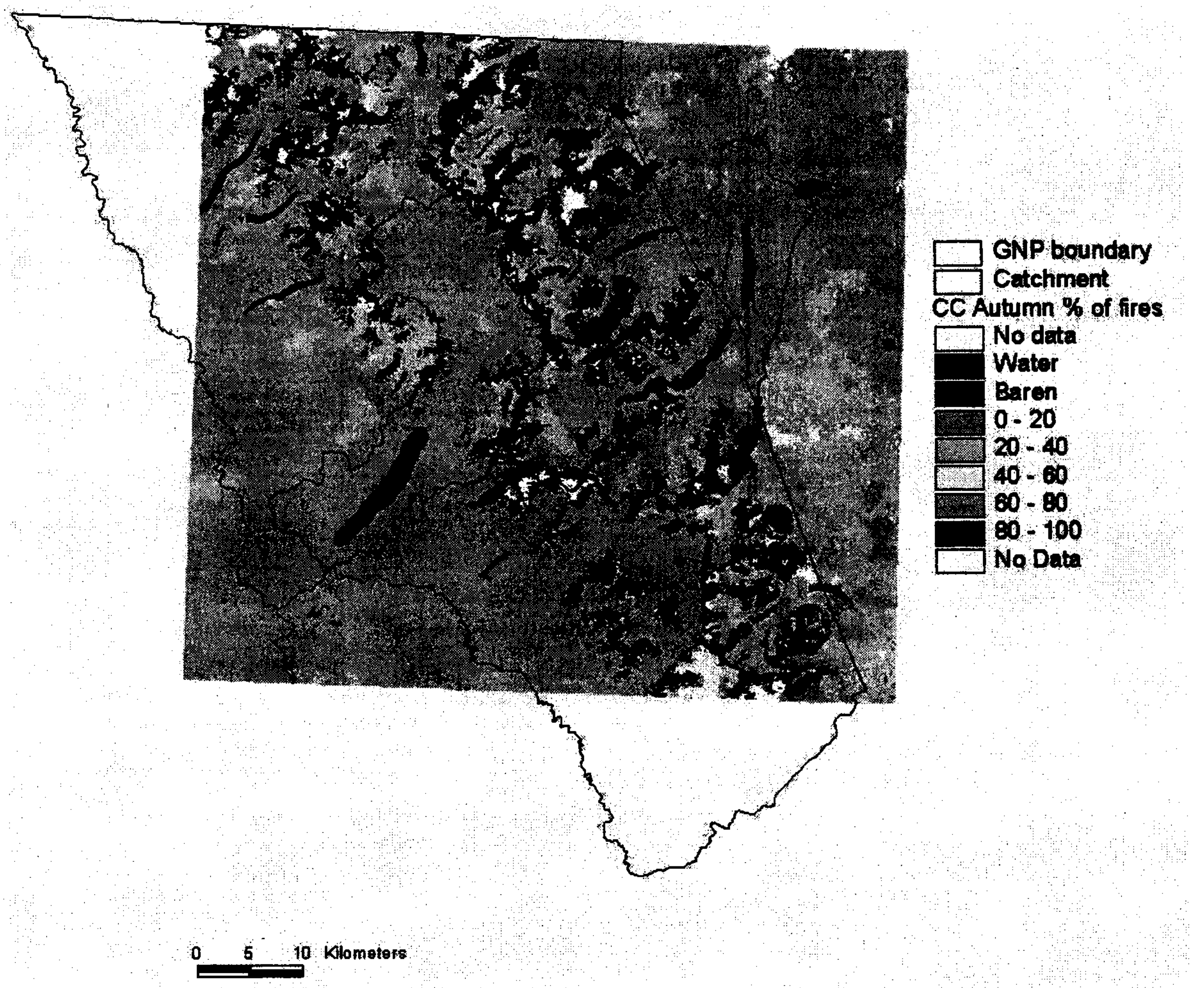


Figure 24c. Average percent of fires in autumn assuming climate change.

**Concluding remarks**

There has been no significant data limitations in the implementation of FIRESCAPE-GNP. As expected, and given the process-based nature of the model, it can generate patterns of fire regime in the Glacier National Park landscape. Some limited calibration of the model to the findings of Barrett *et al.* (1991) has been undertaken but is by no means considered comprehensive. An example of the models application in developing hypotheses concerning the effect of climate change on fire regimes is presented.

The patterns of fire regime presented in this study can only be thought of as hypotheses. They require to rigourous testing against observed data and patterns generated by other models (e.g. FIRE-BGC). Nevertheless, they represent an important step in developing understanding of fire regimes at the landscape scale and, in conjunction with empirical data

(e.g. Barrett *et al.*, 1991), will improve our understanding of the interactions between fire and landscapes in Glacier National Park.

There are two main areas of future research concerning FIRESCAPE-GNP. These are an improved calibaration against empirical evidence and expert opinion, and the inclusion of simple vegetation dynamics.

Calibration against observed data and expert opinion is required to increase confidence in model performance. For example, apart from the spatial patterns in fire regime presented, there are numerous other attributes that can be considered and possible matched against empirical evidence. These include annual number of fires in each of the study catchments, fire size distribution, total area burnt, intensity class distribution etc. Much of the knowledge on these variables is not readily available from the international literature but is often found in reports with restricted circulation and even unpublished observations. Our experience in a similar project (King *et al.*, 2003) which involved implementing FIRESCAPE in the World Heritage area of Tasmania, Australia, indicates that the most efficient means of compiling information of this nature is by a discussion workshop attended by local experts. The objective of a workshop of this nature is to decide on and define critical attributes of the landscape-fire interaction that a model like landscape should be calibrated against. It would also allow facilitate discussion about critical input parameters (e.g. fuel dynamics and ignition probability) that strongly influence patterns of fire regime generated.

The second focus of further research should be developing a simple rule-based succession model. The philosophy of FIRESCAPE is that the most important features of landscape-fire-succession dynamics can be captured using relatively simple approaches. Given this, it is hypothesized that a simple state transition model driven by fire frequency and time-since-fire is preferable compared with the more complex biogeochemical approach adopted by, for example, FIRE-BGC. Again, this approach has proven generally successful for FIRESCAPE-SWTAS in south western Tasmania, also using the mechanism of a workshop with local experts.

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